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# FABRICATION STUDIES FOR T-111 HONEYCOMB STRUCTURE

## FINAL REPORT


Prepared by

S R. Thompson
W. R Young

Approved by

E. E Hoffman


April 15, 1971


prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-13451
A Getz, Project Manager



NUCLEAR SYSTEMS PROGRAMS
SPACE SYSTEMS
GENERAL ELECTRIC
CINCINNATI, OHIO 45215

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NASA-Lewis Research Center
Cleveland, Ohio
A. Getz, Project Manager
Reactor Systems Section

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## FOREWORD

The experimentation described herein was performed at the Nuclear Systems Programs Department of the General Electric Corporation, under NASA Contract NAS 3-13451 Mr. A. Getz of the Reactor Experimental Section, NASA-Lewis Research Center, functioned as the Project Manager

## ABSTRACT

Electron beam (EB) and gas tungsten arc (GTA) welding techniques were investigated to determine the feasibility of manufacturing a T-111 alloy model honeycomb structure. The study model configuration was representative of the core of a compact nuclear power plant assembly. The tentative tube-to-header design of that assembly necessitated that three distinct weld areas be studied, i e , welds joining 1) thin-walled honeycomb tubes to each other along axial lines of contact, 2) thin-walled ring inserts, containing internal projections, to the honeycomb tubes, and 3) relatively massive simulated header components to the ends of the honeycomb tubes Optimum weld conditions were selected by destructive evaluation of parameter study specimens Mechanical properties tests, performed on representative samples, demonstrated the satisfactory load carrying capabilities of each type of weld. Dimensional inspection of subsequent tube-to-tube and tube insert-to-tube sample assemblies, using full length honeycomb tubes, established that distortion from weld shrinkage would be a major difficulty in full scale assemblies. The study also demonstrated that visual examination of the face and root sides of the weld joints could adequately define weld quality Fixtures required to construct full scale model assemblies were prepared and checked out during preparation of full length tube samples.

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# I. INTRODUCTION

The fabrication of the honeycomb core structure of a lithium working fluid, nuclear power plant from the tantalum base alloy, T-111 (Ta-8W-2Hf), requires the development of the techniques to be used in joining the integral components. In accordance with the most recent conceptual design for the power plant, the core structure would contain more than 200 thin-walled T-111 honeycomb tubes, 0.850-inch OD by 0.010-inch wall by 17 inches long, positioned in a hexagonal pattern. Operating requirements dictate that all tubes be metallurgically bonded 1) to each other along common lines of axial tangency, and 2) to a common header flange on one end. The power plant heat source will be cylindrical nuclear fuel elements, inserted in each of the honeycomb tubes. The lithium working fluid will flow axially through the core structure in the annular spacings between each tube ID and the OD of the respective fuel elements, and through the tri-fluted interstices between a group of three tubes Avoiding possible localized overheating from insufficient lithium coolant flow in a restricted volume dictates that the fuel elements be centered in the tubes, and the straightness and roundness of the tubes be maintained over their entire length Thus, each tube must contain sized internal protrusions at specific locations to center the fuel pins and minimize their bowing during service. Flow through the tri-fluted channels will also be regulated by means of limiting orifices machined through the common header flange. Obviously, the joints between the individual tubes, and those between the tubes and the common header flange, must prevent lithium cross-flow.

The overall purpose of the program was to evaluate candidate joining processes and procedures to be potentially applied in the fabrication of the described T-111 honeycomb structure. The temperature/time service

operating conditions for the power plant will be 2200°R for up to 50,000 hours. The candidate joining processes selected for study were gas tungsten arc (GTA) and electron beam (EB) welding. Numerous welding studies on T-111 have indicated that this alloy has excellent weldability.[1] Fabrication of numerous T-111 systems at GE-NSP confirmed this evaluation with the exception of the problem of microcracking which has been observed in multipass GTA welding of material with thicknesses of 3/8-inch or more. No welding of this type was required in this study. Other fabrication techniques, such as brazing, were considered inappropriate, because no foreign materials were permitted in the joint areas. Diffusion bonding was also rejected, primarily because major modifications in existing facilities would be necessary to accommodate full scale hardware assemblies

The specific goals of the program were to develop techniques for producing 1) fuel element spacers in each T-111 tube, 2) welds between tubes, and 3) welds between the tubes and T-111 plate stock to simulate tube-to-header attachments. The design, construction, and checkout of fixtures, needed for preparing representative model honeycomb assemblies, was a further program requirement. Pursuant to weld parameter studies, testing and examination of typical sample weldments were required to establish weld load carrying capacities, and to determine postweld non-destructive inspection methods. Preparation of scaled-up sample assemblies was also necessary to provide data regarding the extent of distortion expected in model assemblies fabrication. This information provided a basis for determining the suitability of the processes and fixtures, and indicated the extent of post-fabrication machining potentially required in hardware assemblies.

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[1] Lessman, G G., Determination of the Weldability and Elevated Temperature Stability of Refractory Metal Alloys, Tasks I and II - The Weldability of Refractory Metal Alloys, WANL-PR-013, October, 1969, p. 3.

# II. EXPERIMENTAL PROCEDURES

## TECHNICAL APPROACH

The T-111 fabrication study program was conducted to determine the feasibility of fabricating the reactor core of the Nuclear Reactor Assembly shown in Figure 1. Two tentative core design configurations were originally considered for study. The tube-to-header design configuration of a 19 tube model assembly, presented in Figure 2, was selected for detailed consideration, in preference to the tube-pad-flange concept, shown in Figure 3, for the following reasons:

1. Components machining costs would be lower.
2. Weld distortion would be minimized because the total amount of welding would be reduced.
3. Difficult to fixture weld joints would be eliminated.
4. Machining after welding would be reduced.

Information, regarding three specific joining areas in a tube-to-header core structure, was required to establish the feasibility of fabricating a full size assembly. Those areas were developing techniques for producing 1) fuel pin spacers in each tube, 2) welds between honeycomb tubes, and 3) attachment of the tubes to a T-111 header.

Each honeycomb tube in the reactor core must contain five stations of three internal projections or fuel pin spacers, equally spaced on the tube ID circumference, also shown in Figure 3.

Three techniques for manufacturing such fuel pin spacers in the tubes were initially contemplated. The first was mechanically indenting the

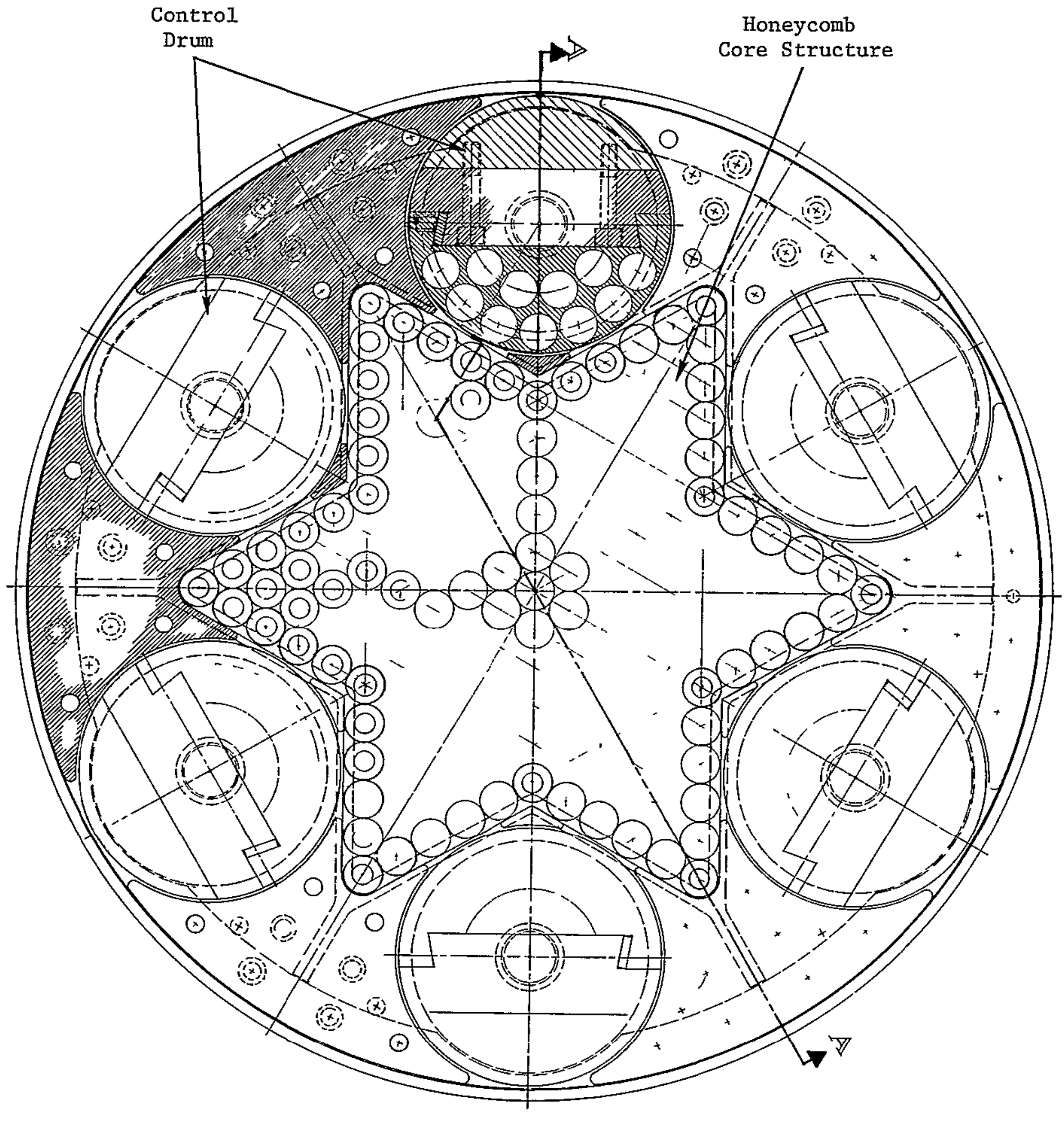
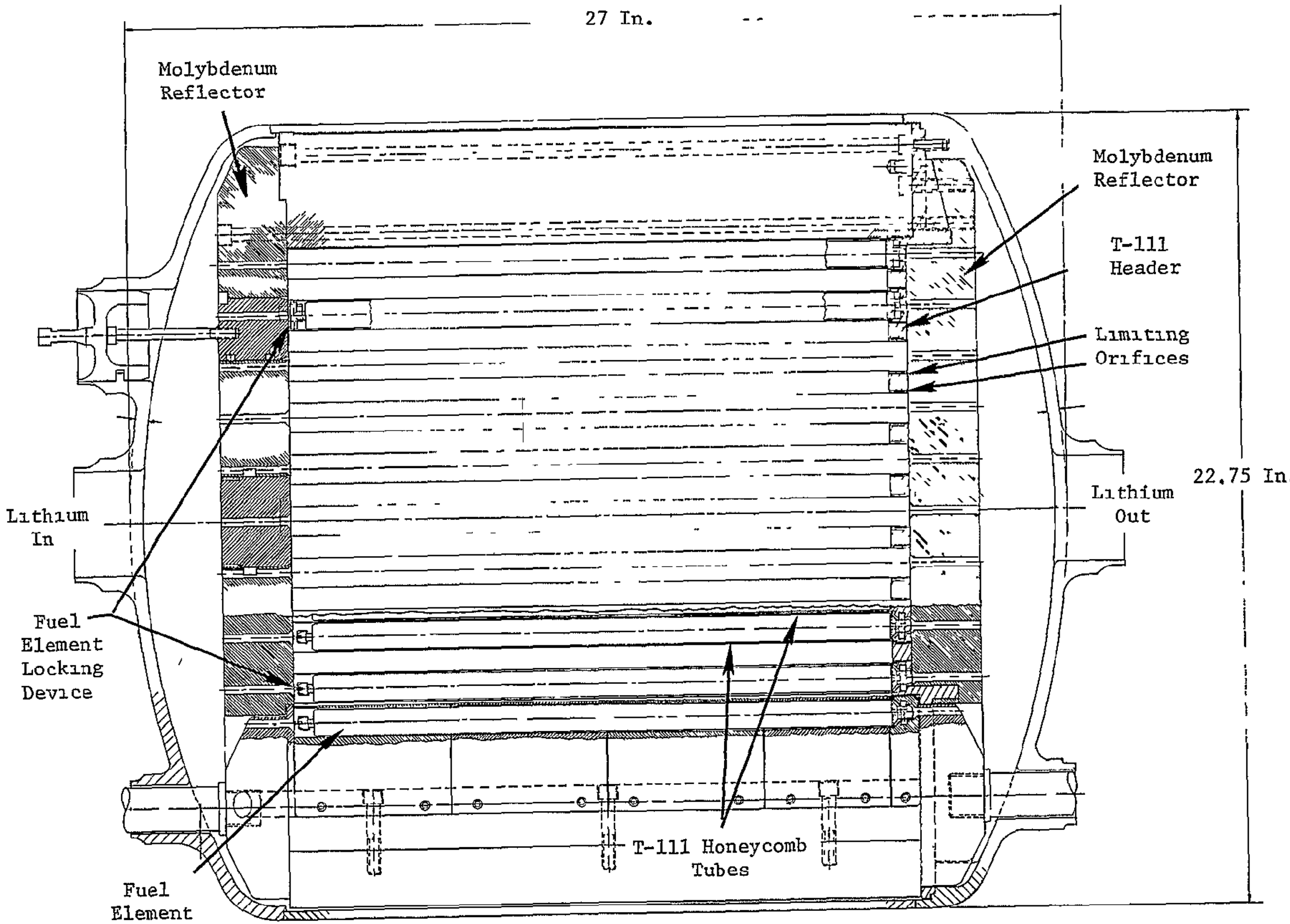



Figure 1. Compact Fast Spectrum Reactor.




Section A-A

Figure 1 (Cont'd). Compact Fast Spectrum Reactor.

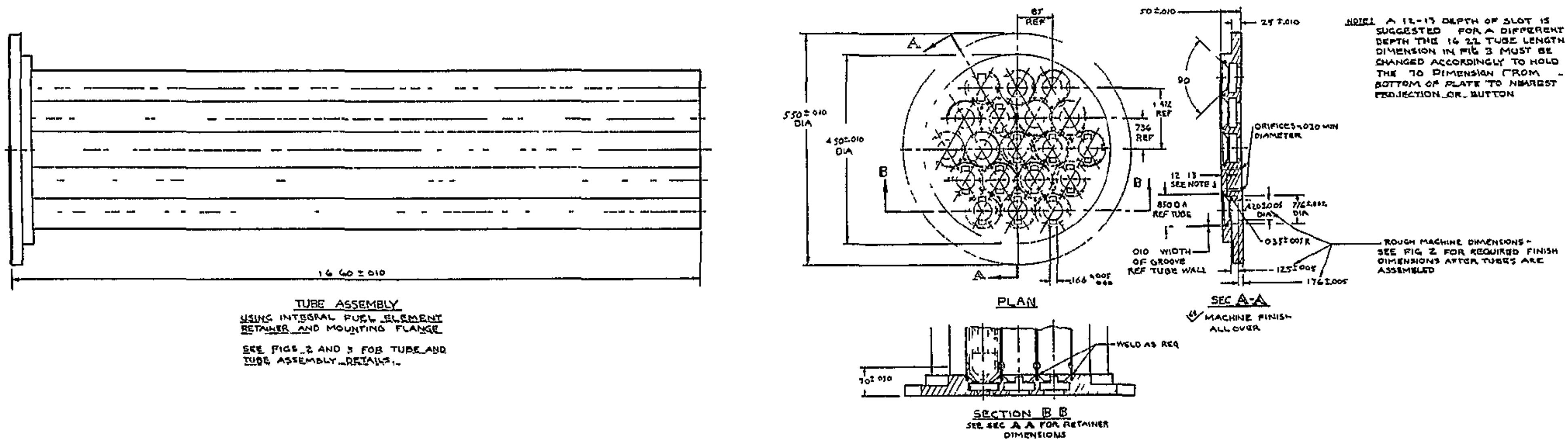



Figure 2. Honeycomb Core Support Structure — Alternate Tube Assembly.

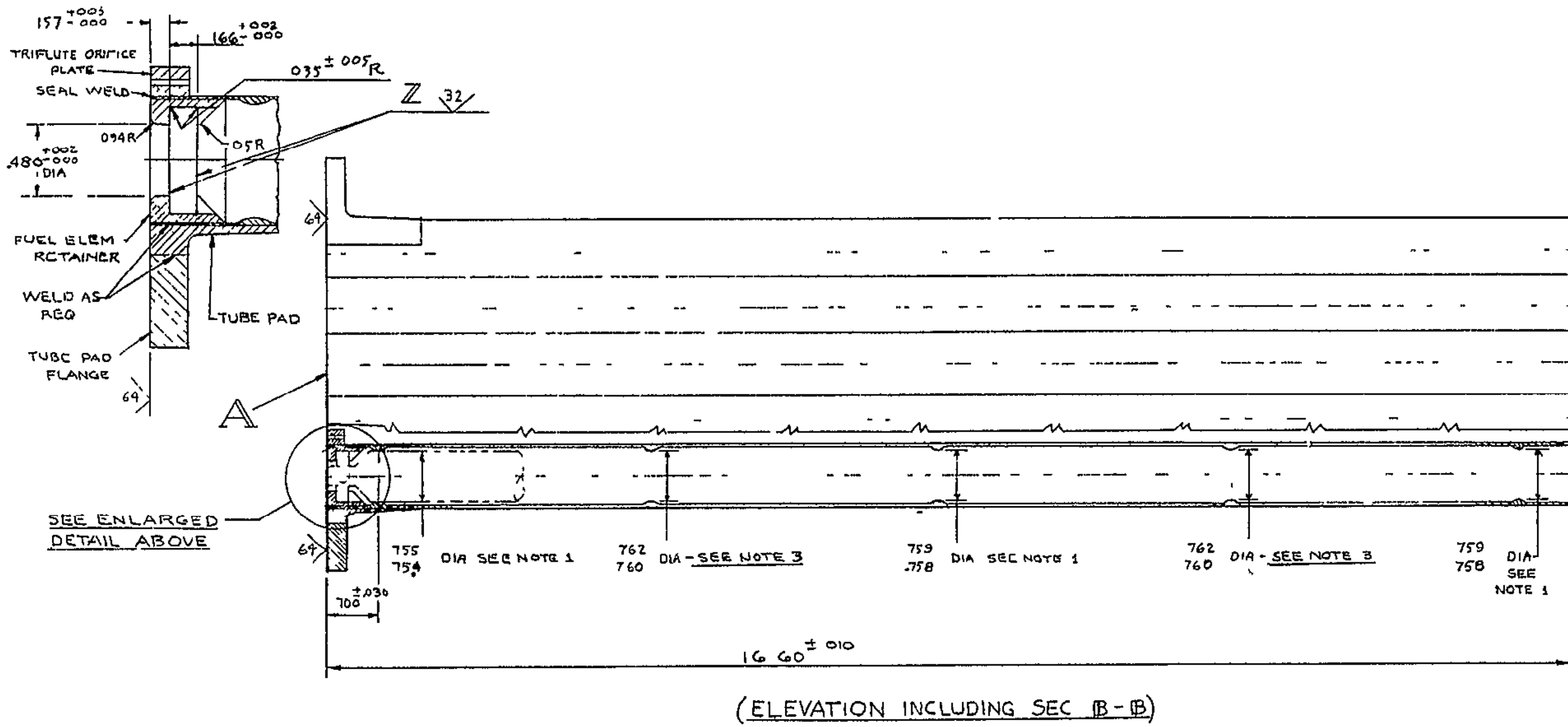



Figure 3. Honeycomb Core Support Structure.

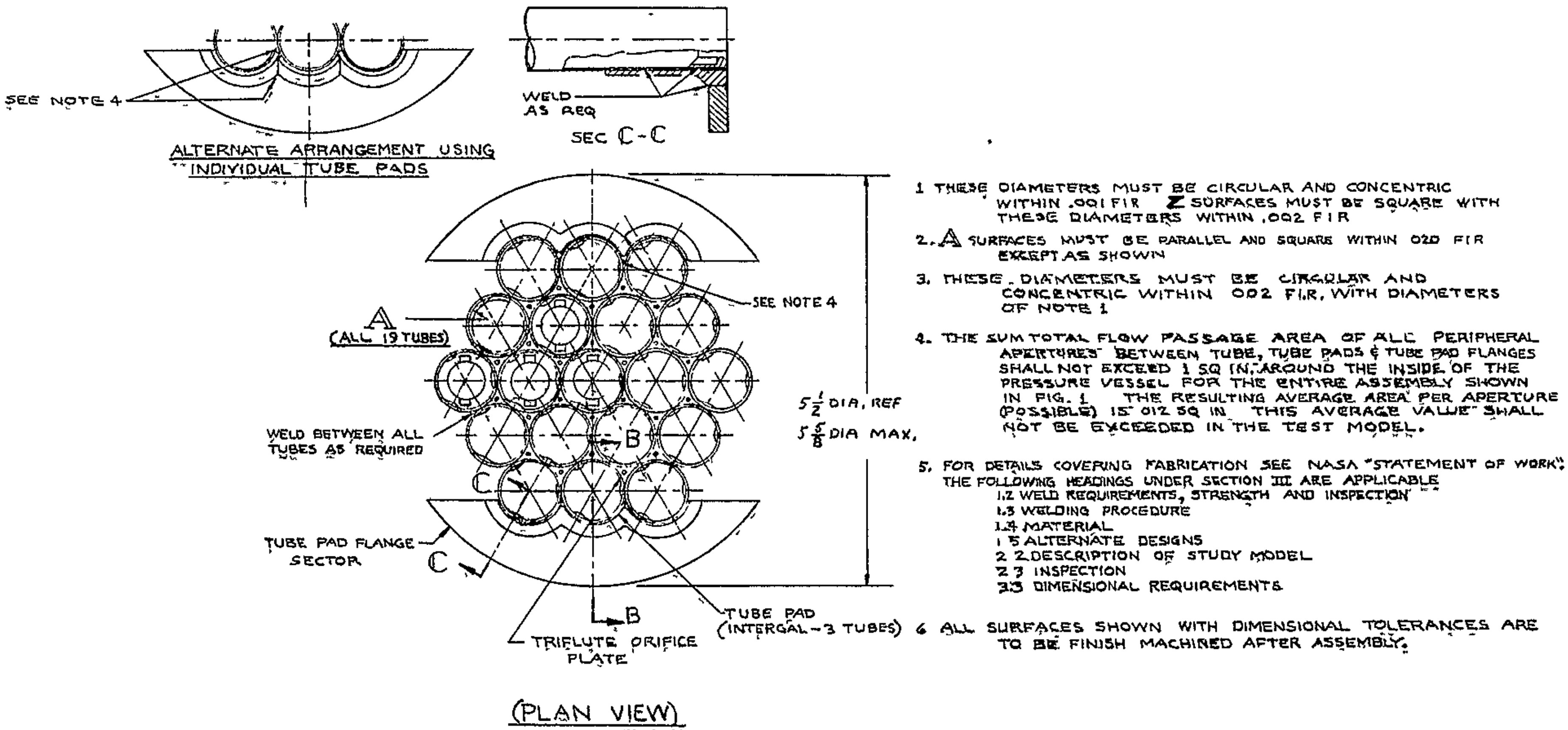



Figure 3. (Cont'd)

tube wall, followed by backfilling of the dimple cavity with T-111 reinforcing material using either an EB or GTA fusion process. The second entailed the insertion of machined T-111 buttons through holes in the honeycomb tube wall, and EB welding around their peripheries for attachment. The third method was indenting and reinforcing (backfilling) short lengths of reduced diameter T-111 tubing inserts (wall doublers), and subsequently EB welding, adjacent to the indentations, to attach them to the 0 850-inch OD tube wall at specific locations. The latter technique was selected for evaluation and development, because it incorporated the best features of the other candidate methods The employment of doublers would result in an assembly configuration having superior strength characteristics at the critical locations adjacent to the fuel element retainers in a honeycomb structure Strengthening the honeycomb tubes at these locations would also reduce the extent of fuel elements bowing, which might tend to occur during reactor operation. The doublers would slightly reduce the fuel element-honeycomb tube ID annular separation, thereby restricting the channels, through which the alkali metal working fluid would flow during operation. This was not considered a significant drawback because of the relatively low pressure drop and lithium flow rate expected in service. Further advantages of the doubler approach were that 1) only a short length of T-111 tubing would be destroyed if a failure occurred during the backfilling process, whereas a complete tube could be lost during reinforcement of indentations in full length tubes, and 2) the expense involved in machining the radius faced buttons would be eliminated To study the indented and backfilled ring insert approach for producing fuel pin spacers, both GTA and EB processes for indentation reinforcement were considered. The different projection depths at various axial tube positions were produced during the backfilling process by employing a special water-cooled molybdenum fixture containing machined recesses, whose configurations matched the respective projection contours. The form and amount of T-111 filler metal, GTA arc voltage and amperage, EB accelerating voltage, beam current, and beam manipulation, were the process variables investigated for indentation reinforcement.

The high voltage EB process was selected for attachment of the doubler inserts to the honeycomb tube wall. Two types of EB attachment

welds were explored, i.e., circumferential welds around each doubler edge, and "circular" welds around each indentation for the spacer to be located at the mid-length of the honeycomb tubes in a subsequent hardware assembly The latter of these welds was considered the most critical structurally, and was therefore required to be capable of withstanding greater shear stresses than the circumferential welds in the service application. Mechanical testing was conducted to insure that the load carrying capability, in shear, of representative welds met or exceeded prespecified values These quality assurance weld specimens were prepared using process variables selected from initial parameter studies data.

Dimensional inspection of a full length honeycomb tube having five inserts EB welded in place, coupled with microstructural examination of single weld samples, were employed to establish the suitability of the process for manufacturing the tubing ID protrusions. The fixture used during EB welding was required to 1) maintain desired contact of the inserts with the tubing wall without producing an excessive "heat sink" effect, 2) not interfere with the insert rings indentations and 3) be removable subsequent to the welding operation. A special, expandable molybdenum mandrel was designed and fabricated to fulfill those fixturing requirements during doublers attachment to full length tubes. That design configuration was based on data obtained from initial program EB welding trials with shorter tube sections.

Three different processes were initially considered for producing the axial tube-to-tube metallurgical bonds, i.e., automatic GTA and EB welding, and diffusion bonding. The latter two methods were rejected as candidates in this feasibility study primarily for the following reasons: First, EB welding could not be utilized completely in the buildup of multiple (more than 3) tube assemblies because some joints would be inaccessible, second, the diffusion bonding method would present high materials and fixtures costs, in addition to the possibility of destroying a complete assembly during the elevated temperature bonding cycle Alternately, the GTA technique could be used for joining any number of tubes because the welding torch could be placed inside an individual tube. Further, such welds could more readily be nondestructively inspected for

quality than EB welds, potentially using only visual examination In addition to these reasons, the GTA process was considered the most reliable means for producing multiple tube-to-tube joints exhibiting satisfactory strength, while resulting in minimum distortion.

The initial exploration of tube-to-tube GTA welding consisted of parameter studies to establish the effects of welding current, electrode shape and positioning, shielding gas, and travel speed on the resultant welds. These parameters were varied to establish those which yielded the desired weld characteristics, relative to the tubing distortion. The results were also used to define the type and extent of fixturing required for welding of multiple tube assemblies. Thereafter, additional samples were prepared to determine the spacing between tubes which could be tolerated during the welding process. Selected specimens were inspected using visual, ultrasonic, radiographic and dye penetrant techniques, prior to their sectioning for microstructural examination. The results obtained were used to evaluate the welding conditions, and to establish necessary postweld nondestructive inspection methods. Other samples were prepared for subsequent mechanical testing to certify the shear load carrying capacity of tube-to-tube weldments. Finally, a full length, seven tube array was assembled on prepared fixtures, and welded using the developed optimum conditions, to determine the extent of tubing distortion, reliability of the welding process, and suitability of the welding fixtures employed. Those fixtures were designed for usage in the tube-to-tube joining for a 19 tube model assembly.

The investigation of tube-to-header joining was conducted using only single tube and simulated header specimens. The geometry of the simulated header components was modified, from that initially conceived, until a configuration amenable to welding was developed. The automatic internal GTA welding process was also selected for evaluation to produce satisfactory tube-to-header joints. A special tungsten arc torch for this internal tube welding was designed, fabricated, and mated with a motor drive head. In addition to the header joint configuration changes, the process variables of electrode shape and position, welding current and rotational travel speed were systematically evaluated. After satisfactory weld conditions had been realized, additional specimens

were prepared using a fixture, which held the corresponding tube and header in desired relative positions. These tests were conducted to simulate conditions at the header weld joints in a multiple tube assembly, in which the tubes had been previously bonded to each other. All weld specimens were visually inspected for weld contour and surface defects, and selected samples were submitted for microstructural examination to assist in the determination of optimum welding parameters. Three weld specimens, prepared using the established optimum conditions, were mechanically tested to certify their load carrying capacities.

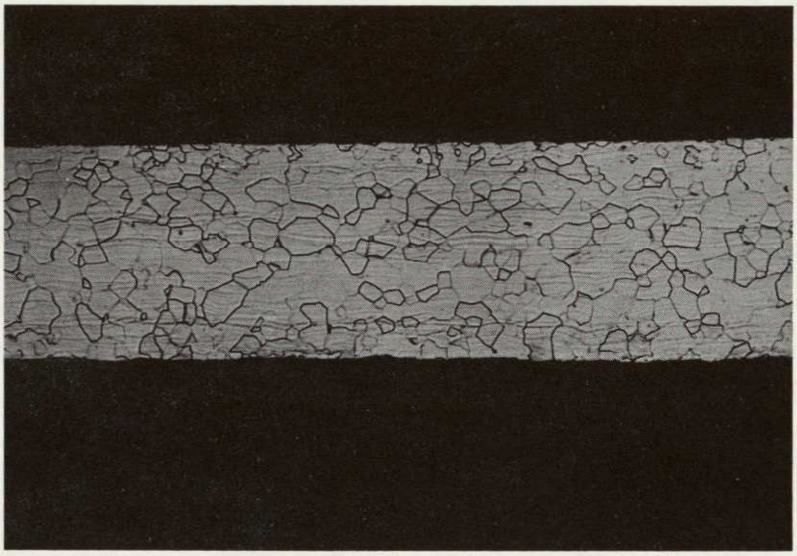
All fixtures and materials, required for the fabrication of a 19 tube T-111 model honeycomb structure (see Figure 2), were supplied to NASA-LRC for further trial efforts. The sequence and details of some processing operations, tentatively to be used in the fabrication of such model assemblies, were generated as a result of this study program. Also identified were other fabrication areas needing further investigation or development to complete the assemblies.

## MATERIALS AND PROCESSES

### MATERIALS PROCUREMENT AND QUALITY ASSURANCE

The T-111 alloy tubing, 0.850 inch OD by 0.010 inch wall by 18 inches long, used in this program was supplied by NASA-LRC per specification C-393643. A section of the as-received tubing was submitted for metallographic examination to ascertain whether the prior vendor processing had produced the desired microstructural characteristics. The examination indicated that the T-111 material had not received a final 3000°F/1 hour thermal cycle, normally required to produce the best heat treat condition for T-111 alloy components prior to welding. The remaining tubes were therefore exposed at 3000°F/1 hour before being used in this welding investigation. A typical microstructure of this tubing after heat treatment is presented in Figure 4.

Three representative, as-received, T-111 tubes were dimensionally inspected to determine variations in their straightness, circularity and wall thickness. These measurements, as shown in Table I, indicated that the diameters were consistent within ± 0.002 inch, and no sizing of tubes



100X

Figure 4. Microstructure of 0.850-Inch-OD x 0.010-Inch-Wall T-111 Tubing After 3000°F/1-Hour Heat Treatment (Longitudinal Section). (G56012A) Etchant: $NH_4F$, $HNO_3$, $H_2O$

TABLE I

MEASUREMENTS OF AS-RECEIVED T-111 HONEYCOMB TUBING

| Tube[1] Number | Outside Diameter Measurements (Inches) at Indicated Distances From One End of Tube: 2 Inches | 4 Inches | 6 Inches | 10 Inches | 14 Inches | Wall Thickness Measurements at End of Tube (Inches) |
|---|---|---|---|---|---|---|
| 77 | 0.8505 | 0.8503 | 0.8522 | 0.8508 | 0.8500 | 0.0102 |
| | 0.8513 | 0.8506 | 0.8515 | 0.8515 | 0.8518 | 0.0105 |
| | 0.8500 | 0.8515 | 0.8503 | 0.8505 | 0.8521 | 0.0102 |
| | 0.8511 | 0.8510 | 0.8503 | 0.8505 | 0.8500 | 0.0108 |
| | (Overall tube bow = 0.004 inch) | | | | | |
| 75 | | 0.8510 | 0.8524 | 0.8519 | 0.8505 | 0.0100 |
| | | 0.8512 | 0.8510 | 0.8512 | 0.8500 | 0.0103 |
| | | 0.8520 | 0.8512 | 0.8524 | 0.8525 | 0.0100 |
| | | 0.8525 | 0.8518 | 0.8523 | 0.8525 | 0.0108 |
| | (Overall tube bow = 0.010 inch) | | | | | |
| 78 | | 0.8522 | | 0.8540 | 0.8533 | 0.0110 |
| | | 0.8530 | | 0.8535 | 0.8535 | 0.0112 |
| | | 0.8535 | | 0.8520 | 0.8525 | 0.0110 |
| | | 0.8530 | | 0.8522 | 0.8525 | 0.0115 |
| | (Overall tube bow = 0.006 inch) | | | | | |

Maximum Variation in Outside Diameter = 0.8535 - 0.8500 = 0.0035 Inch

Maximum Variation in Wall Thickness = 0.0115 - 0.0100 = 0.0015 Inch

Variation of Specific Tube Inside Diameter: Tube #77 - 0.8292 to 0.8310 Inch
Tube #75 - 0.8292 to 0.8317 Inch
Tube #78 - 0.8296 to 0.8311 Inch

(1) Tubing Material Control Number - MCN 18A-001-(1 to 133)

would be necessary for their usage in the construction of a multiple tube-to-common header hardware assembly. However, some slight axial bowing was observed (maximum of 0.010 inch), which pointed out that maintaining the required axial contact between tubes for tube-to-tube welding would necessitate bundling in some instances.

In addition, thirteen of the 133 supplied T-111 tubes were visually inspected at 10x to check for possible surface defects. Nothing of a rejectable nature was observed, although a few minor pits and/or scratches (~ 0.0005 inch maximum depth) were detected on the outside surfaces of some tubes. No further quality assurance testing was performed on the tubing material.

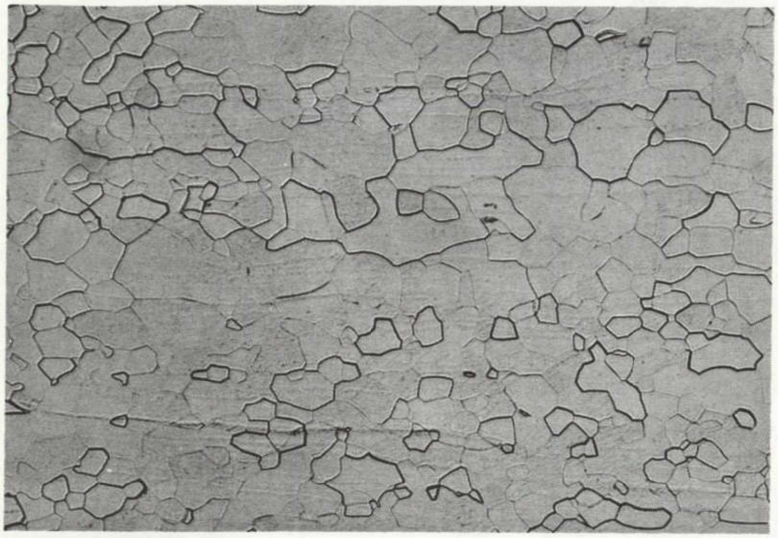
The 0.625-inch thick T-111 plate material, required for program studies and eventual usage in fabrication of 19 tube model honeycomb assemblies, was procured per GE-NSP Specification 01-0040-02-D. Confirming quality assurance testing of this plate stock consisted of interstitial gas analysis, metallographic inspection, and determination of tensile properties. The results of these analyses indicated the acceptability of the procured material. Typical microstructures of the T-111 plate are shown in Figure 5. The molybdenum and stainless steel materials, used for welding fixtures, were procured to applicable GS-NSP specifications; no quality assurance testing was performed on these materials.

## WELDING, ASSOCIATED PROCESSES, AND EQUIPMENT

The gas tungsten arc (GTA) and electron beam (EB) welding employed in this T-111 investigation, were conducted in accordance with the following NASA specifications:

1. C-393666-1, "Welding of Columbium, Tantalum, and Their Alloys by the Tungsten Arc Process," 2-18-69.
2. C-393666-4, "Electron Beam Welding Refractory Metals and Their Alloys," 2-18-69.

The cleaning of T-111 components for welding, and required postweld annealing treatments, were done in accordance with NASA Specifications, C-393666-2 and C-393666-3, respectively.



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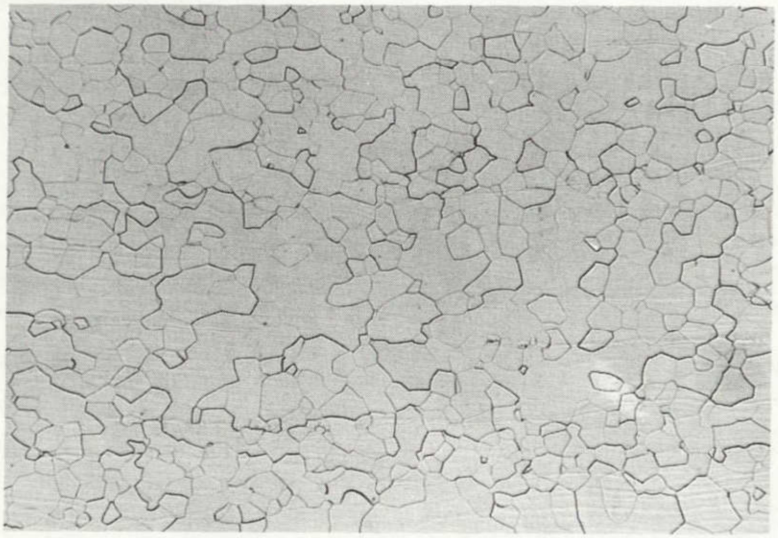

Mag.: 100X

Figure 5. Typical Microstructures of As-Received 0.625-Inch-Thick T-111 Plate Stock (Top-Longitudinal, Bottom-Transverse). (H46011A & H46021A) Etchant: $NH_4F$, $HNO_3$, $H_2O$

## GTA Welding Equipment

The GTA process was used for tube-to-tube and tube-to-header weld studies, and for backfilling of indentations in fuel pin spacers to provide reinforcement. The vacuum-purged, water-cooled, inert gas-filled welding chamber is shown in Figure 6. The helium fill gas was purified by passing sequentially over molecular sieve and heated titanium. The oxygen and water vapor levels in the gas were reduced to less than 1 ppm each by that method. The helium supply and purification train for this have been described in a prior report.[2] The chamber atmosphere was analyzed before welding for oxygen, nitrogen, hydrocarbons, and water vapor, using an electrolytic hygrometer and gas chromatograph, shown in Figure 7. Welding was initiated if the analyses indicated concentrations of oxygen, nitrogen, and water vapor less than 5, 15, and 10 ppm, respectively. During extended welding operations or tests, these impurities were monitored appropriately, to insure against the potential contamination of the T-111 alloy. The arc welding machine employed is depicted in Figure 8. That machine supplied automatic programmed, constant direct current, power for welding and provided up and down current slope control. Special voltage- and current-limiting features of the machine were beneficial to prevent destruction of an assembly by welding machine malfunction. The GTA welding of both tube-to-tube and tube-to-header assemblies was conducted automatically, using impulse arc initiation and selected timed delays at the start of a cycle. These capabilities were also integral electronic portions of the welding machine circuitry. Manual GTA techniques were employed for reinforcement of doubler indentations. The fixtures used for the inert gas welding will be described, in relation to the specific areas studied, in later sections of this report.

## EB Welding Equipment

High-voltage EB welding techniques were studied primarily for attachment (circumferential and circular welds) of reduced diameter ring inserts, or doublers, to the wall of the basic honeycomb tubing. The method was also briefly used to explore potential backfilling of doubler indentations. The high-voltage (150 kv-6 kw) machine is depicted in

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[2] Lyon, T. F., Purification and Analysis of Helium for the Welding Chamber, NASA-CR-54168, July 1, 1965, p. 25.

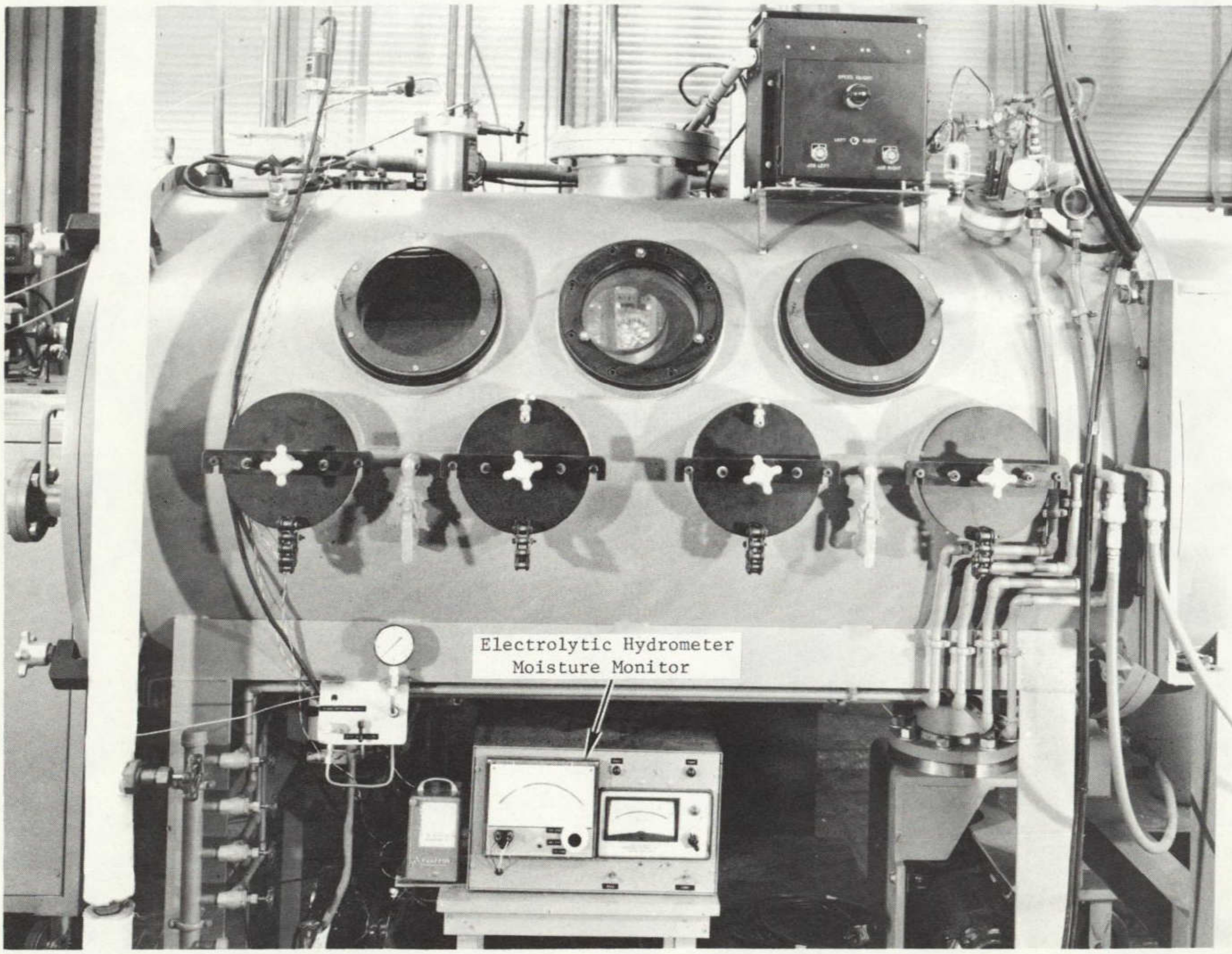



Figure 6. Vacuum Purged Inert Atmosphere Welding Chamber - 3 Ft Diameter x 6 Ft Long. (C65040928)

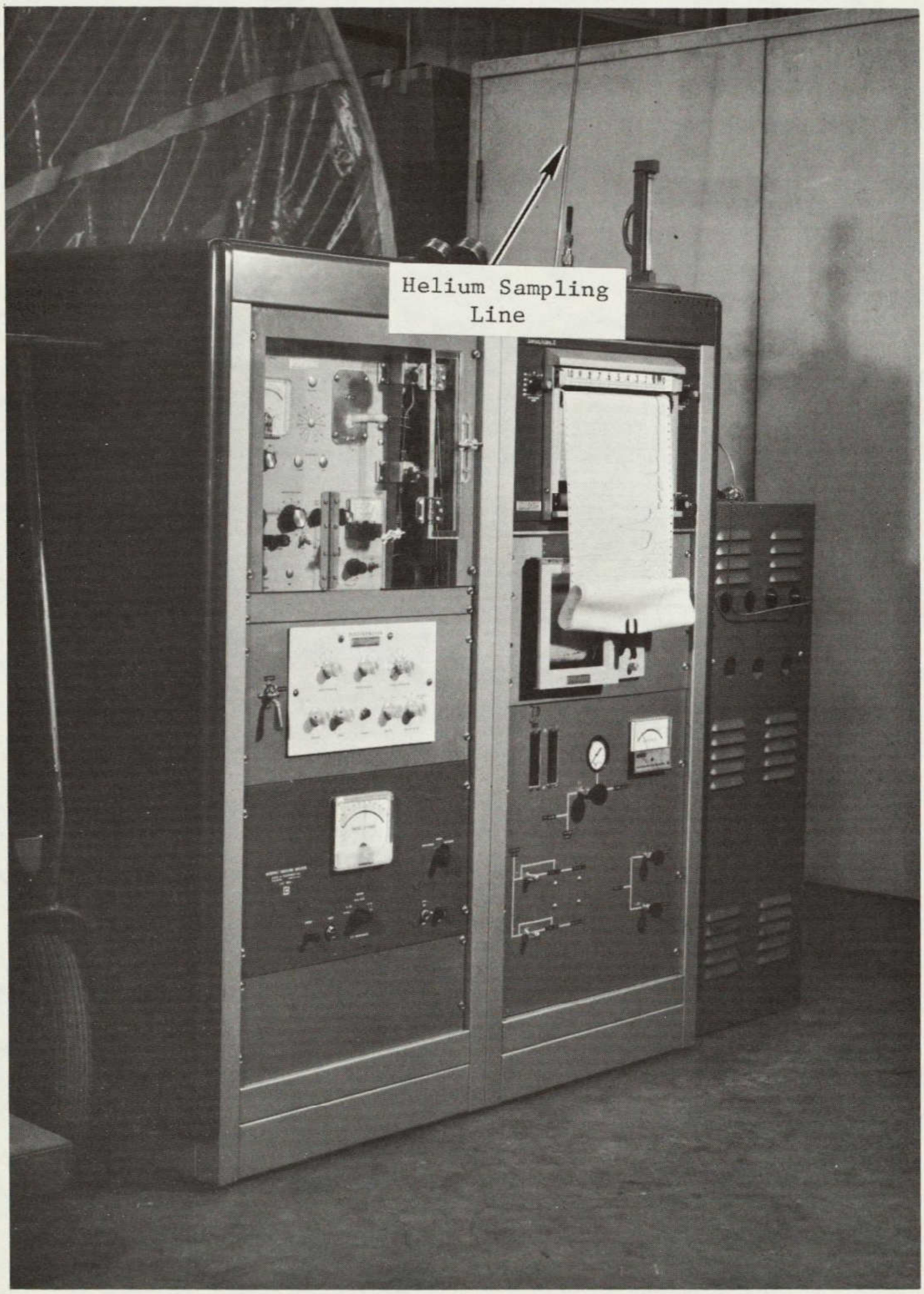



Figure 7. Gas Chromatograph for Analysis of Helium in the GTA Welding Chamber. (P68-9-44B)

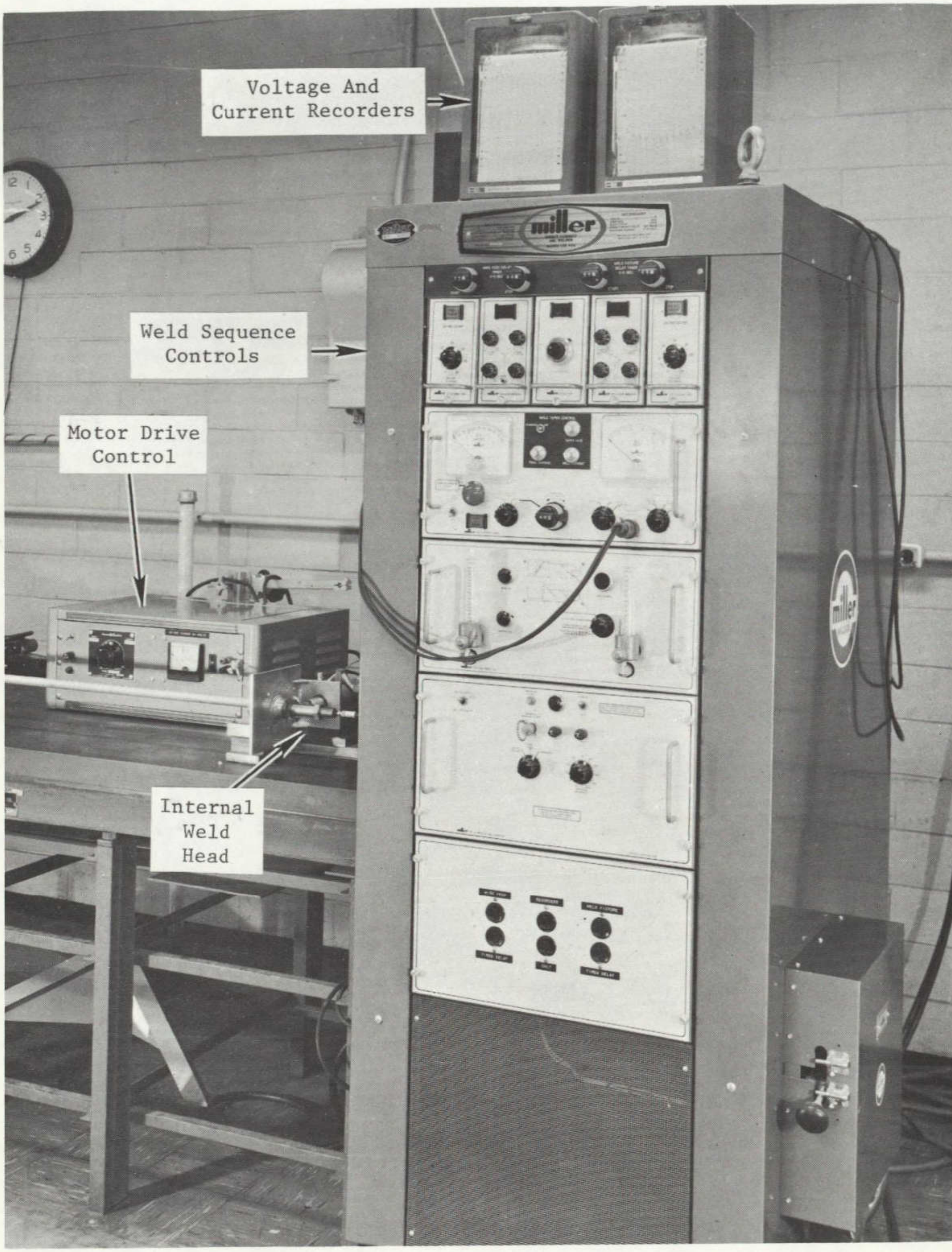



Figure 8. Automatic Tungsten Inert Gas Welding Machine Controlled Welding Sequences. (C67020850)

Figure 9. The circumferential welds were made using a rotating chuck, which is an integral part of the basic EB welding unit. An externally located beam polypattern generator was also used to puddle the T-111 reinforcement material in the doubler indentations, and to a limited extent for beam modulation when studying the circular EB doubler attachments.

## Postweld Annealing

The postweld annealing of selected specimens was performed in the cold wall vacuum furnace shown in Figure 10. These specimens were wrapped with Cb-1Zr foil prior to annealing to prevent possible environmental contamination during the furnace cycles.

## Inspection Test Equipment

The inspection of representative weld joints, by destructive and nondestructive methods, was performed to establish satisfactory nondestructive techniques to be used for inspection of prime hardware assemblies. The nondestructive testing methods and equipment used for inspection included the following:

1. A Sperry No. 721 Reflectoscope with a 50 w pulser-receiver and a special search unit for pulse-echo ultrasonic inspection of tube-to-tube welds.
2. A GE No. OX250 X-ray unit with an 85 to 250 kv, 10 ma, peak capability, for radiographic inspection of tube-to-tube welds.
3. A GE model M-60 helium mass spectrometer for helium leak testing of tube-to-header welds.
4. A borescope for visual examination of internal weld surfaces.
5. A booth for fluorescent penetrant inspection of exterior weld surfaces.

Destructive metallographic examination of specific samples was performed and compared with nondestructive results to establish the degree of data correlation, and thereby the acceptable nondestructive method to be employed for subsequent weldments.

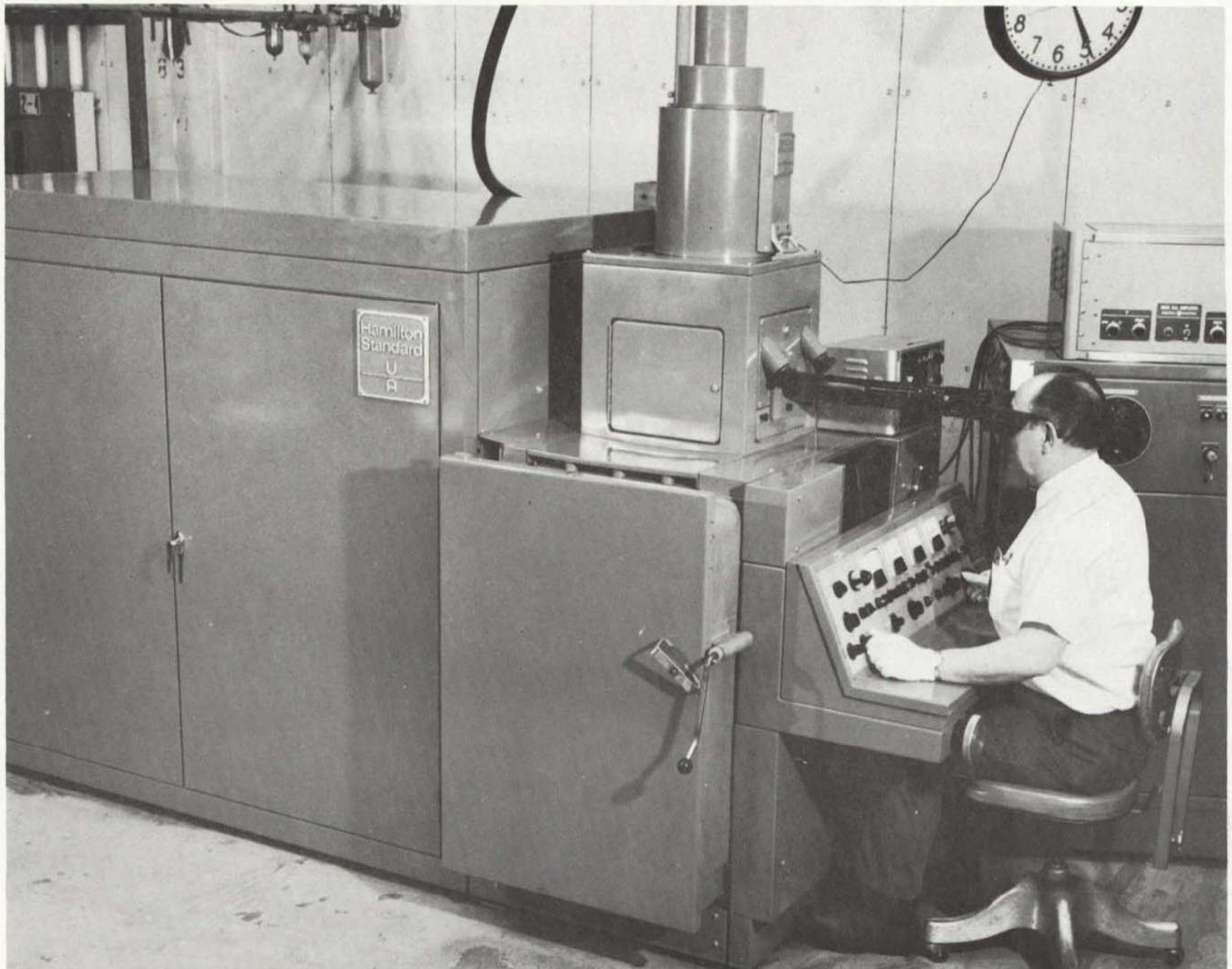



Figure 9. High Voltage Electron Beam Welder, 150 KV, 6 KW. (P69-2-3AG)

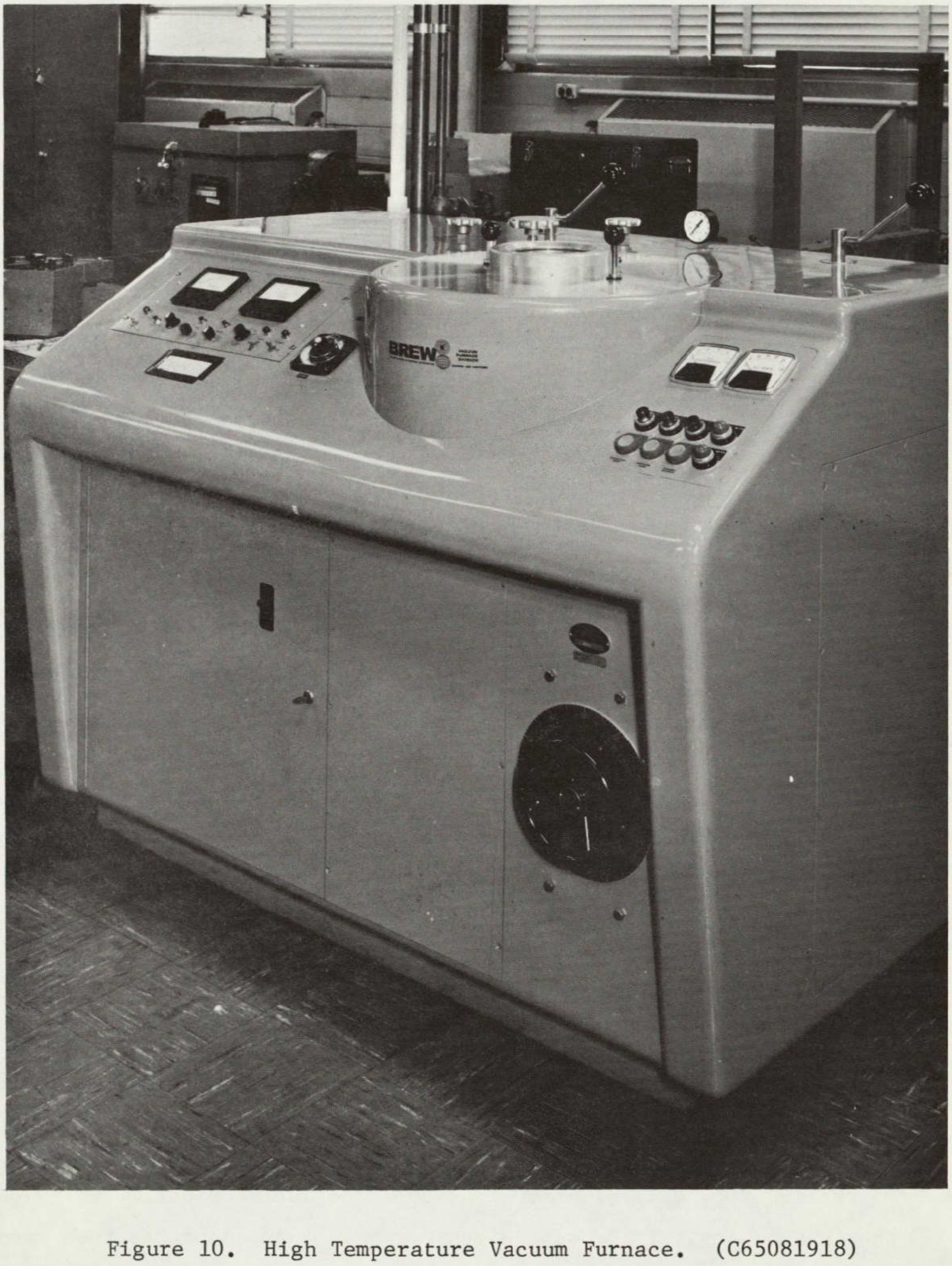



Figure 10. High Temperature Vacuum Furnace. (C65081918)

## WELDING PROCEDURES

The three joining areas of the honeycomb core support structure investigated were fuel pin spacers fabrication and tube-to-tube and tube-to-header welding. Each of these areas were studied separately to develop techniques which could be directly applied in the fabrication of an integrated model assembly. Evaluation of initial weld samples established optimum welding conditions, which were used in processing of further specimens to determine distortion effects in samples more representative of the final hardware assembly. The fixtures, required for the fabrication of a 19-tube model assembly (refer to Figure 2), were defined, constructed, and checked for effectiveness by preparing these latter specimens. Welding equipment modifications were made, as required, to facilitate the welding operations. Dimensional examination of welded specimens was used to determine the extent of postweld machining, or process alteration, potentially necessary to compensate for welding distortion in the fabrication of a multiple tube-to-common-header model assembly. Ensuing paragraphs will describe the procedures used in studying each of the above indicated joining areas.

### Fuel Pin Spacers Fabrication

The method, selected for development to produce fuel pin spacers in the 0.850-inch-OD by 0.010-inch-wall T-111 honeycomb tubes, involved the use of dimpled and reinforced ring inserts or wall doublers. Usage of the tube doubler technique required the investigation of methods for 1) mechanically indenting reduced diameter ring inserts to produce three equally spaced internal projections around their periphery, 2) backfilling of the doubler indentations with T-111 reinforcing material, and 3) EB welding to attach the inserts to the honeycomb tube wall at five separated axial stations. The desired contours of the projections are depicted in Figure 11; note that the diameters at the projection nodes are different, dependent on the axial station along any tube. The method chosen to achieve those depths involved indenting each insert to a single fixed depth, and then utilizing the heat produced during backfilling to cause the insert material to sag and conform to the shape of machined recesses in a water-cooled molybdenum fixture. The pattern of the EB attachment welds for doublers in full-length honeycomb tubes is indicated in Figures

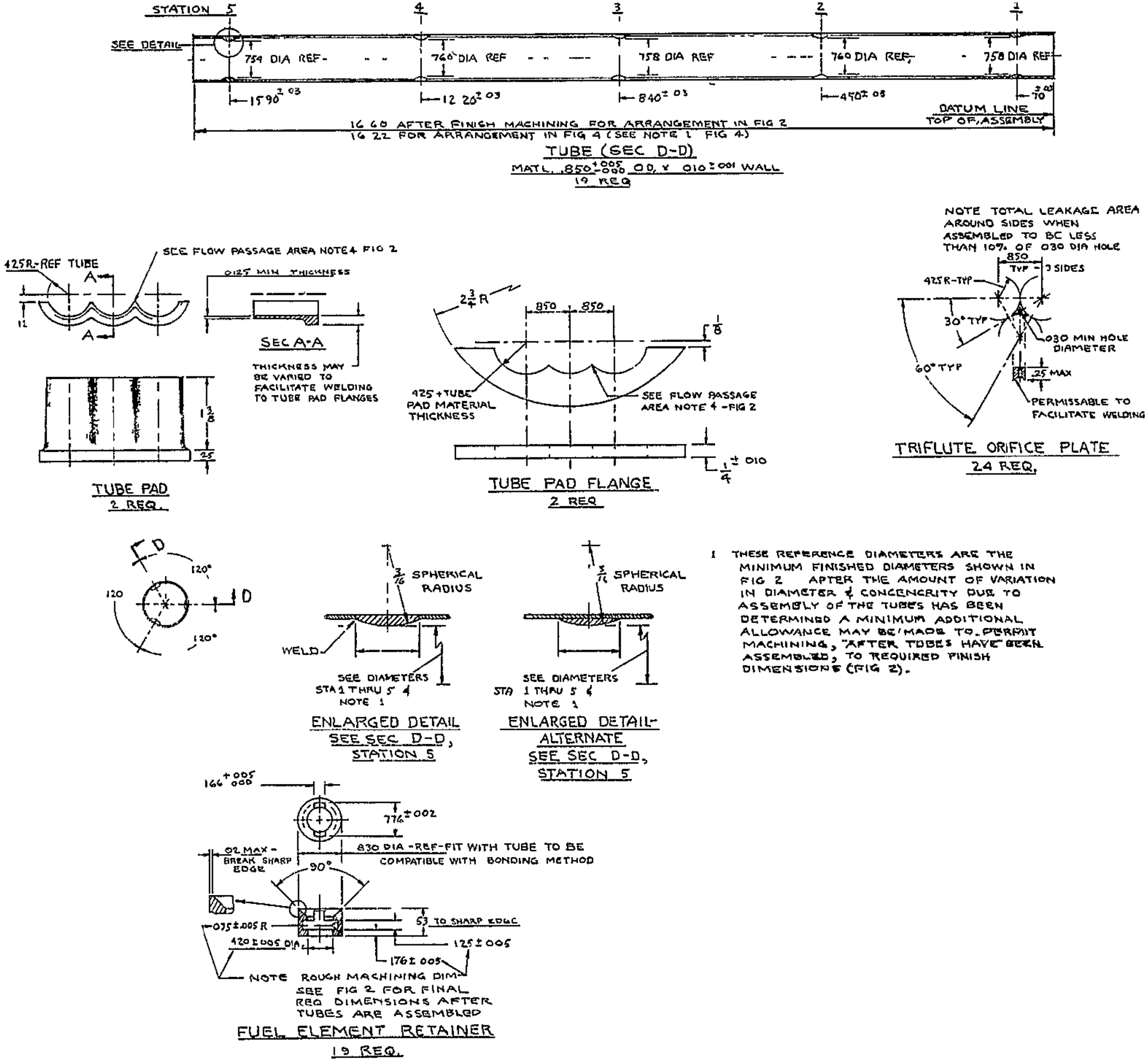



Figure 11. Details - Honeycomb Core Support Structure.

12 and 13; two cylindrical and three circular welds are required for the doublers at the tube midpoints, while only two cylindrical welds are needed at other doubler locations. Note that the section view, shown in Figure 12, displays the doubler positioned closest to the header, in accordance with one of the various design modifications conceived during the study program. Figure 13, indicates the positions of the circular and circumferential welds in relation to an indentation in the center tube doubler

## Indentation Procedure

Several of the as-received T-111 tubes were cold drawn to a 0.827-inch OD and cut into selected lengths (0.5-inch for the majority of trials), to provide material needed for inserts. As indicated in later paragraphs, longer inserts were needed to facilitate tube joining to relatively massive header components. A sufficient number of inserts were indented to provide those needed for backfilling experiments and potential fabrication of a 19-tube model assembly The indenting fixture is schematically shown in Figure 14, it consists basically of a stainless steel die with a 0.83-inch-diameter cylindrical bore, a stainless steel ram and backup ram, and three hardened steel spherical balls at partially recessed locations in the die body The ball recesses in the die body are axially tapered to permit ball retraction before removal of an indented ring. The general dimpling procedure was as follows.

1 With the balls in position for indenting, insert the backup ram in the die cavity,

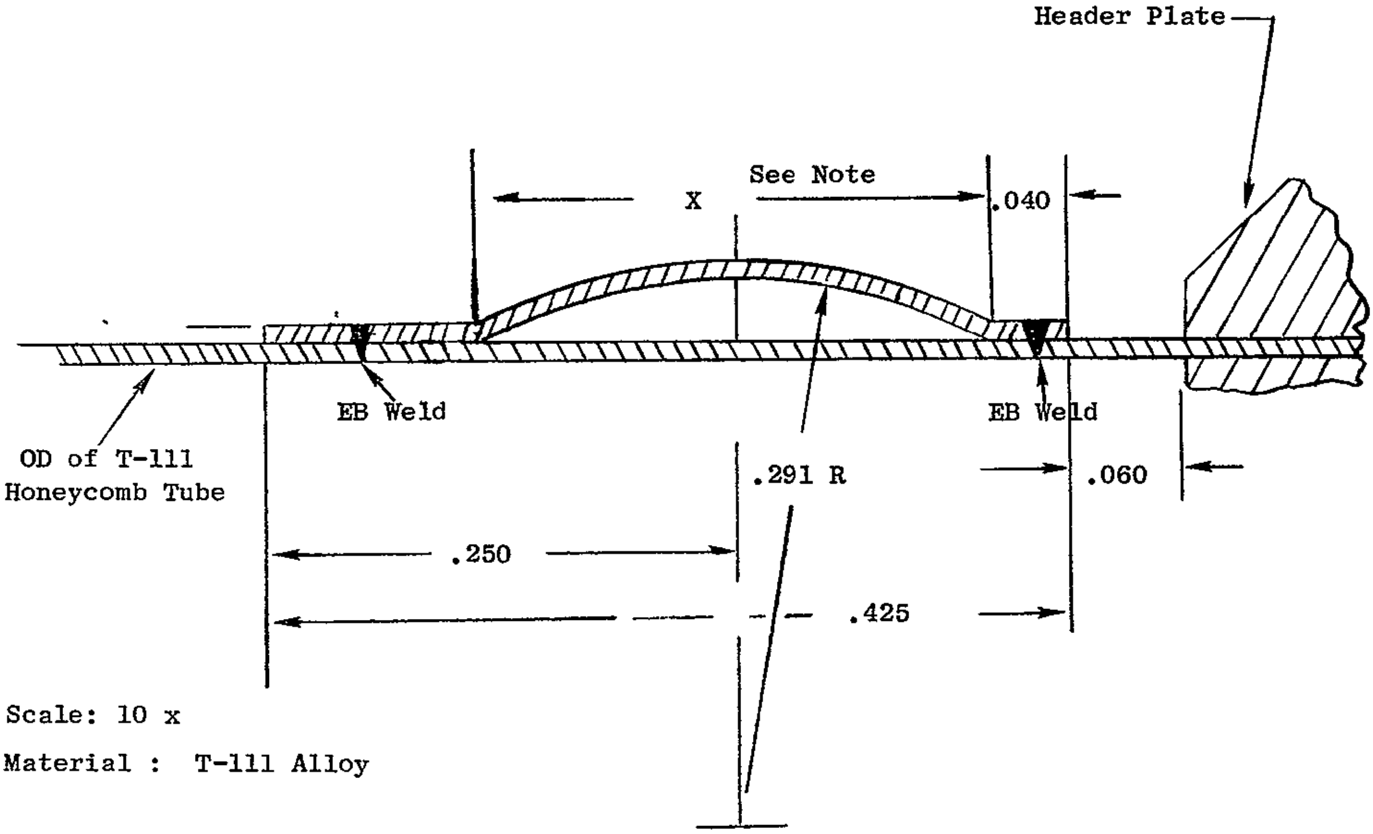
2. Place the cylindrical T-111 insert atop the backup ram,

3 Place a loose-fitting cylindrical rubber stopper in the insert ring,

4 Insert the ram until contact is made with the top of the rubber stopper,

5. Apply sufficient pressure to the ram (~ 10,000 psi -gauge pressure on a hydraulic press) to cause radial upsetting of the insert, thus causing it to conform to the contour of the distended ball surfaces;

6. Remove pressure and withdraw ram and backup ram,




NOTE: X Dimension varies with diameter tangent to button surfaces.

Doubler at tube end nearest header plate shown - Remaining doublers are 1/2" wide and symmetrical about 0.250 inch-centerline and as shown.

Figure 12. Interim Conceptual Design Configuration of Insert Doublers in T-111 Honeycomb Tubes.

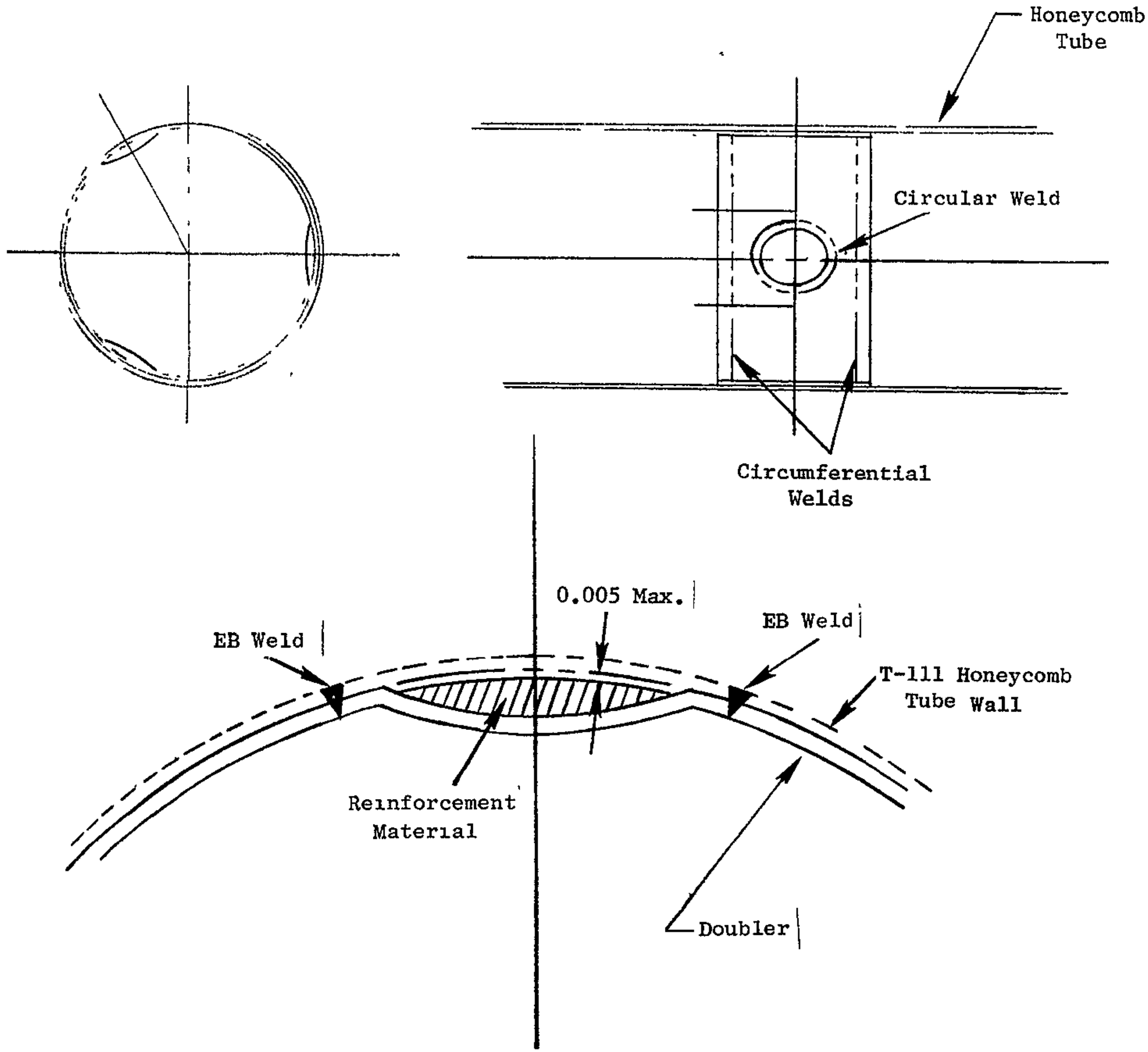



Figure 13. Pattern for EB Weld Attachment of Doublers at Mid-Length of Honeycomb Tube.

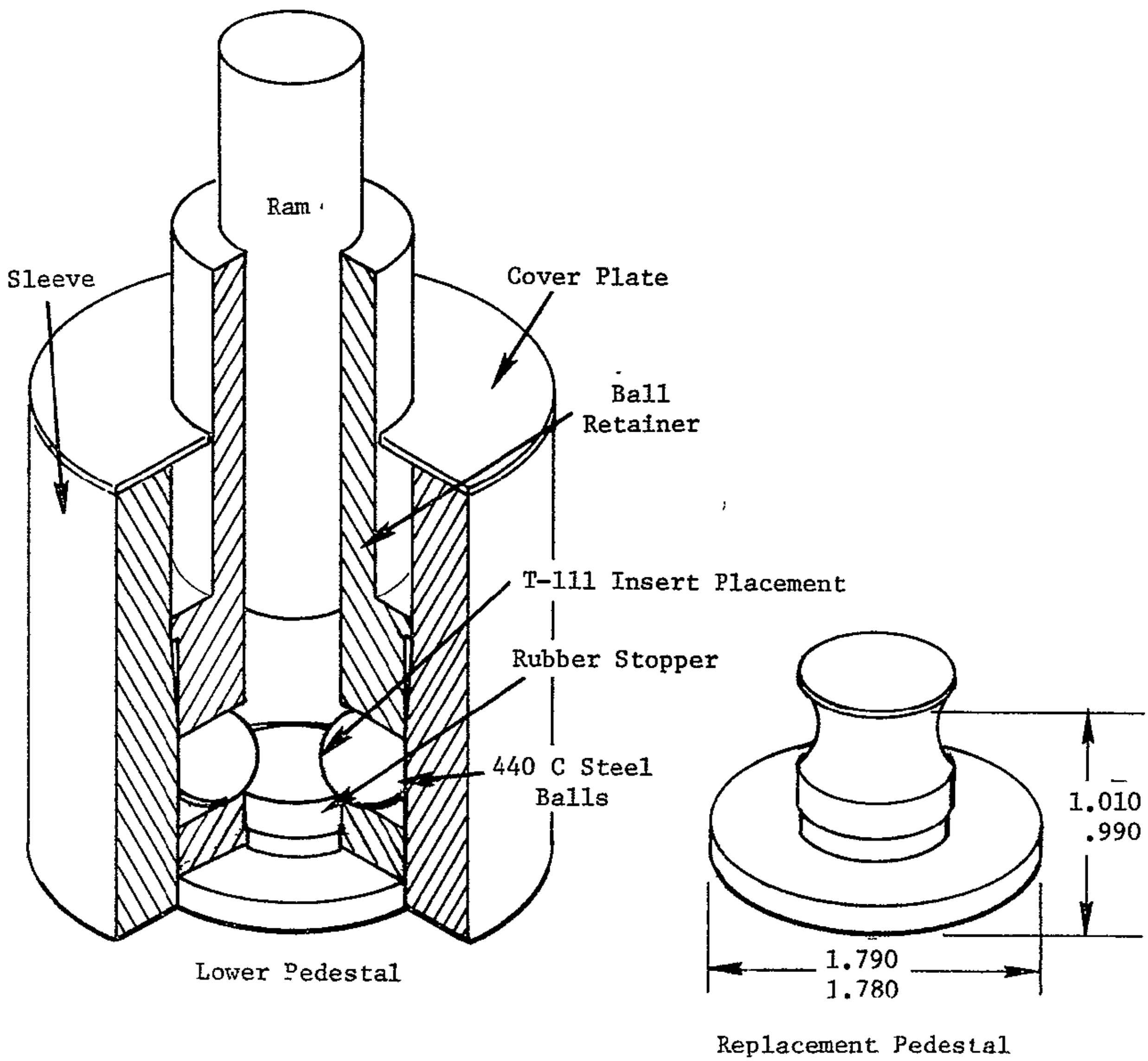



Figure 14. Fixture for Indenting 0.83-Inch-OD T-111 Inserts.

7. Push out formed inserts after retracting the balls,

8. Repeat steps No. 1 through No. 7 for preparing additional insert rings.

All inserts were cleaned after forming by degreasing with acetone and ethyl alcohol, and then pickled in a nitric-hydrofluoric-sulfuric acid solution. The majority of the formed inserts were prepared for follow-up experimentation at NASA-LRC.

## Indentation Backfilling Methods

The electron beam process was the first method investigated for backfilling reinforcement of the doubler indentations. The geometric requirements for the depth and contour of the reinforced dimples are specified in Figures 12 and 13. The basic procedure consisted of melting T-111 reinforcing material in the dimpled OD surface of the doublers. The beam accelerating voltage and current were adjusted to produce a molten puddle. The T-111 backing material was preplaced in the indentation in the form of small chips. Examination of the initial samples prepared by this process indicated several problems which were cause for investigating an alternate method for the backfilling operation. Later paragraphs, indicating the results of all backfilling experiments, will describe these problem areas.

The gas tungsten arc method was investigated as an alternate for backfilling doubler indentations, because of the difficulties associated with the EB filling process. A chill fixture was designed and fabricated for use during the GTA backfilling operations to avoid catastrophic melting of the insert walls. The fixture, shown in Figure 15, consisted basically of a water-cooled molybdenum bar containing machined recesses, over which the indentations were positioned for backfilling. The contours of the machined recesses matched the different geometries of the internal doubler surfaces at the indentations. The copper, water-cooling lines on the back of the main molybdenum piece, were attached by brazing at 1820°F with a gold-18% nickel braze alloy. The usage of the chill fixture simplified the overall task for producing doublers because only a single tube indenting fixture was necessary.

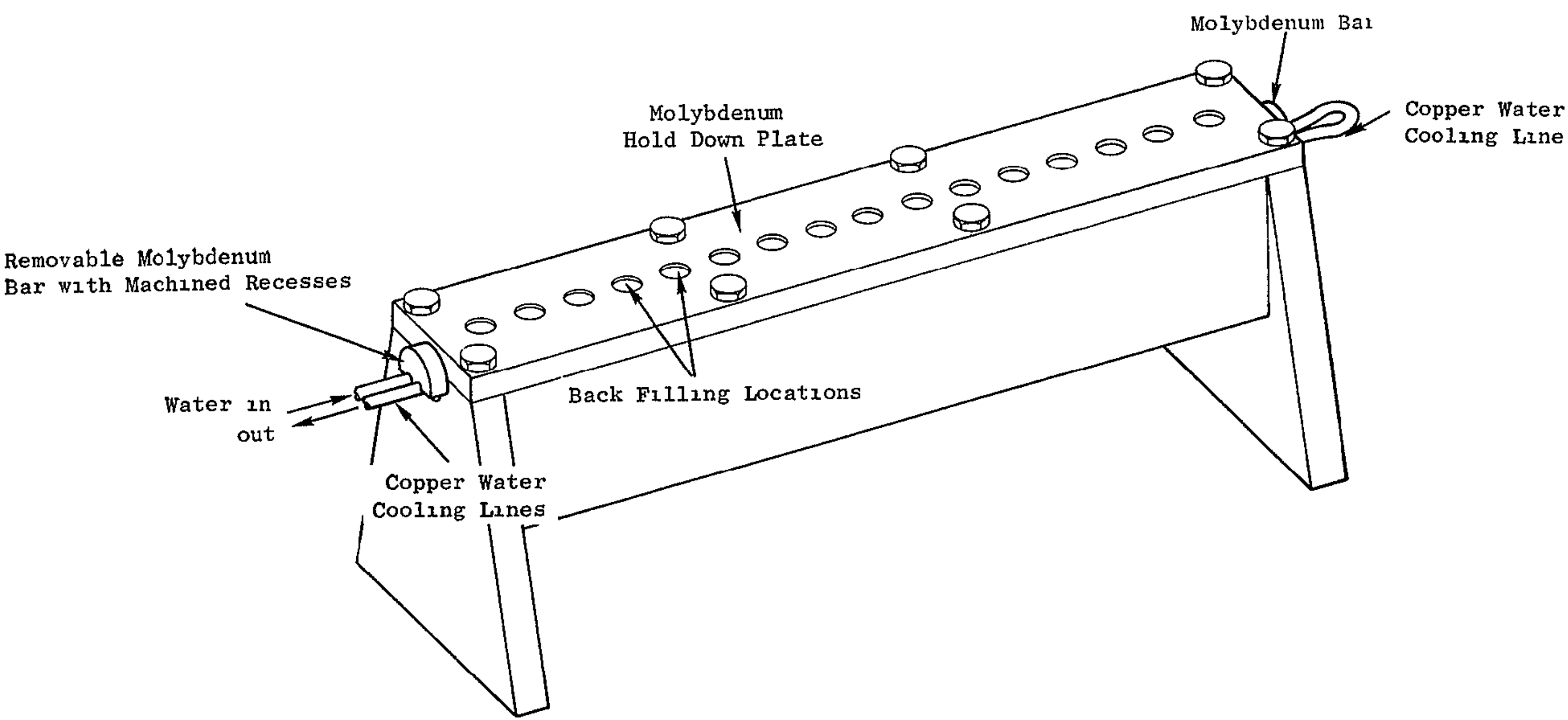



Figure 15. Sketch of the Water-Cooled Fixture Used for Backfill Reinforcement of Doubler Indentations.

The GTA doubler reinforcement experimentation was conducted using manual control of the welding heat and preplacement of the T-111 backing material into the doubler dimples. A 0.062-inch-diameter tungsten electrode and helium fill gas were used for all trials, measured lengths of 0 062-inch-diameter T-111 filler were cut, dependent on the depth of the indentation being filled. The individual lengths were then formed into spherical balls by applying heat from the welding torch. The spherical T-111 filler was then placed in the appropriate indentation for backfilling. The desired melting and flow of the filler in the dimple cavity was achieved by gradually increasing the welding current to 140 amps with the electrode positioned over the center of the indentation. Spiral motion of the welding torch was used to produce the necessary puddling action and filling of the dimple cavities. After reinforcement, the rings were sized to produce a uniform outside diameter, using the previously described indenting fixture (balls retracted), with a replacement pedestal, or lower ram (shown in Figure 14) in position. The sizing process was the same as that used for indenting the ring inserts, the replacement lower ram positioned the inserts above the plane of the indenting balls. Several of the prepared ring inserts were sectioned through the protrusions for microstructural examination to certify that the desired filling characteristics has been obtained.

## Insert Welding Methods

The procedure for development of the electron beam process to attach reduced diameter inserts to the honeycomb tube wall consisted of 1) preliminary parameter studies with short tube sections and single inserts, 2) selection of optimum welding conditions from metallographic inspection data, 3) preparation and mechanical testing of specimens welded using the developed parameters to certify load carrying capabilities, and 4) preparation and dimensional inspection of a full-length honeycomb tube, having doublers welded in place at five separated axial positions, to determine distortion effects. A special, segmented and axially sectioned, expandable mandrel, molybdenum fixture was designed and fabricated to implement the EB welding operations. One section of that fixture, and the tapered drive pin, constructed for welding in full-length tubes, is shown schematically in Figure 16. The fixtures were axially split along

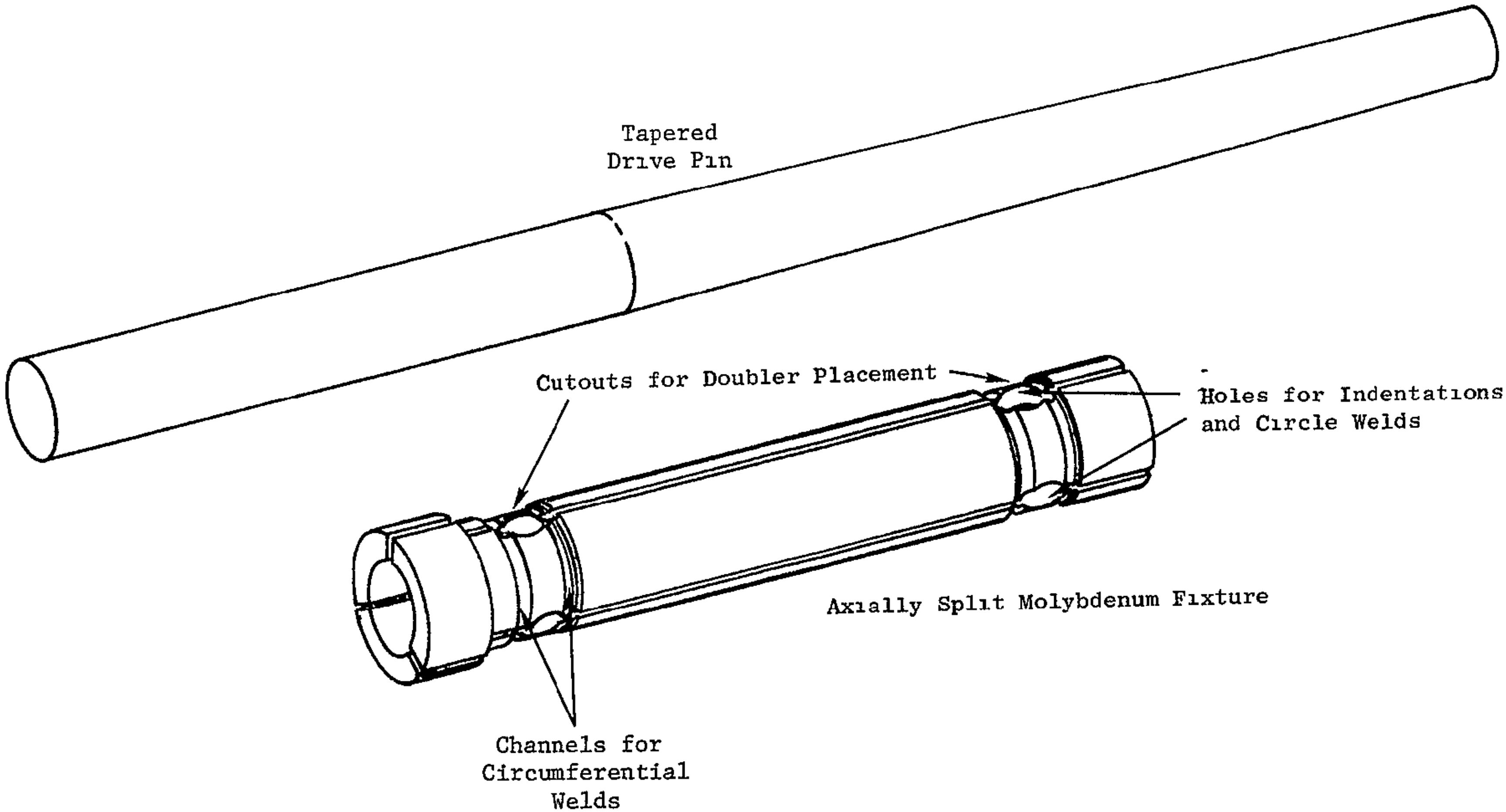



Figure 16. Section of the Expandable Molybdenum Fixture, With Tapered Drive Pin, Used in Electron Beam Welding of Doublers to Honeycomb Tubes.

three radial planes to permit their removal from the tubes after welding, the fixtures also were machined in the areas directly under the weld lines to prevent possible bonding of the tubes to the fixture. The following sequential steps were used in EB welding:

1. Assemble the doubler, split mandrel, and tapered drive pin,
2. Slide the doubler and mandrel assembly into the honeycomb tube to preset positions,
3. Apply pressure to one end of the drive pin to produce the necessary contact between the doubler and tube;
4 Place the exposed end of the drive pin in the chuck of a rotating drive inside the welding chamber,
5. Evacuate the chamber to less than 5 x $10^{-5}$ torr and weld.

The process variables of beam current, accelerating voltage, deflection, modulation, and rotational speed were investigated during parameter studies.

## Test Specimen Procedure

Representative parameter study specimens were metallographically examined through both circular and circumferential welds to select best conditions for subsequent preparation of three mechanical test specimens. An approximately 3-inch length of the reduced diameter tubing was used for each of those specimens, along with an equal length of the standard 0 850-inch-OD tubing. Holes were machined through one end of each tube section to provide for insertion of load transmission pins needed in mechanical testing. The smaller diameter tubes were inserted in the standard tubes to produce a 3/8-inch overlap prior to EB welding. The first mechanical test specimen was fabricated using a single circumferential weld; the remaining two specimens contained three equally spaced circular welds each. Figure 17 depicts the three mechanical properties test specimens. All three samples were postweld vacuum annealed at 2400°F/1 hour before tension testing. The sample, containing the circumferential EB weld, was included for testing to establish a quantitative measure of weld transverse shear strengths. This information was necessary because 1) axial loading of the samples, having

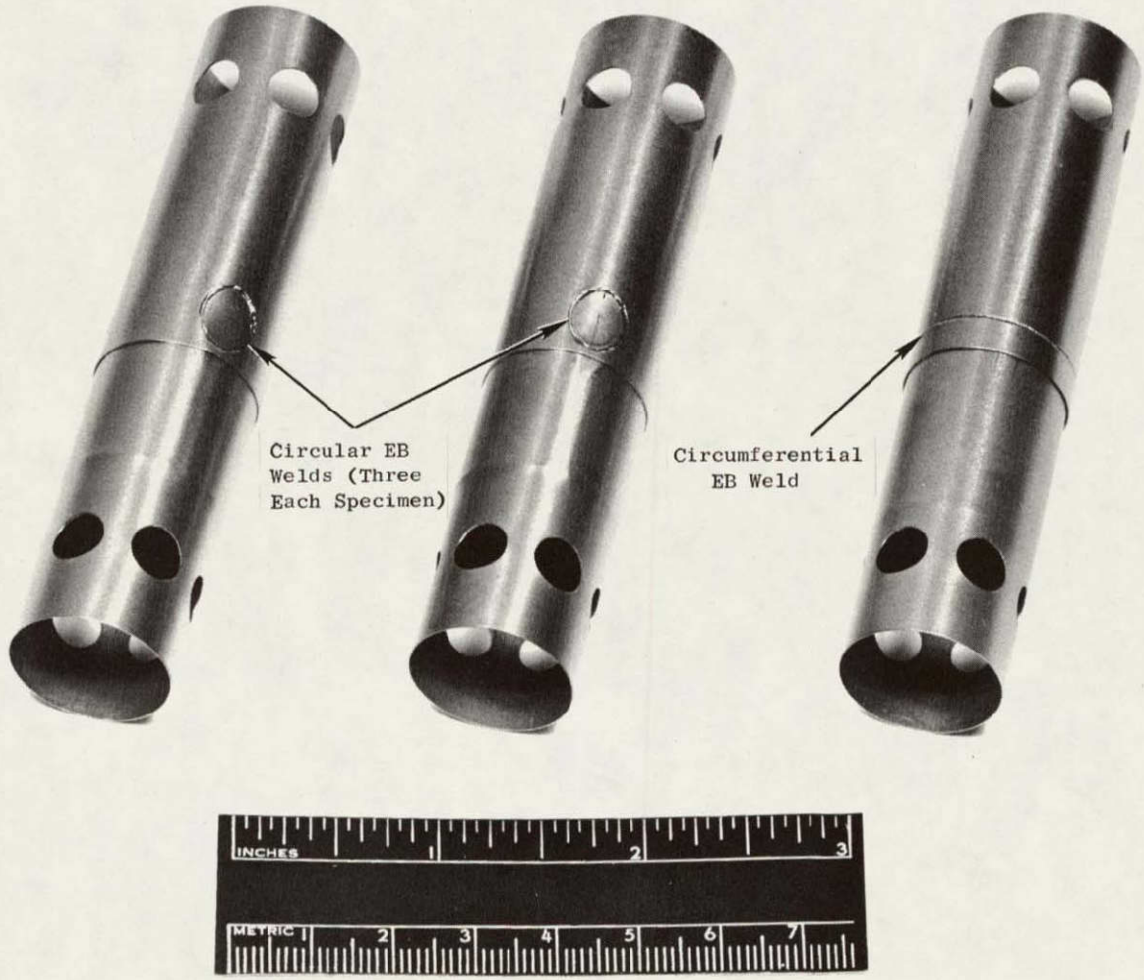



Figure 17. T-111 Tube Insert-to-Tube EB Weld Specimen for Mechanical Properties Testing - Before Test. (70-4-3B)

circular weld attachments, made such a determination impossible, and 2) the stresses induced across the circular welds during hypothetical service exposures would be transverse shear in nature. After mechanical testing had certified the acceptability of the welding parameters, a full-length honeycomb tube and five indented and backfilled inserts were prepared for additional EB welding trials. Those doublers were welded to the tube at predesignated locations along its length. The pattern of the welds was identical with that previously specified for fabrication of model assemblies. The tube was dimensionally inspected to determine the effects of doublers welding on tube distortion (roundness and straightness).

## Tube-to-Tube Welding

### GTA Welding Procedure

The internal, automatic, gas tungsten arc welding process was selected for study to develop a method for bonding 0.850-inch OD by 0.010-inch wall T-111 tubes to each other along common lines of axial contact. The GTA process variables of welding heat input, fixturing, travel speed, spacing between tubes, and welding electrode position, were evaluated by the fabrication and inspection of various tube-to-tube weld samples. The choice of the optimum shielding gas was to be based on results from sample welding conducted in helium and argon environments, while maintaining otherwise identical preparatory conditions. However, only welding in a helium atmosphere was performed, based on the consideration of the maximum current which the welding torch could carry, as indicated below. The effects of doublers on the axial tube-to-tube welds was documented by preparing additional samples, which contained EB attached inserts in each tube. The desired intertube contacts for GTA welding were obtained by wire strapping in preliminary parameter experiments; later welding trials were conducted using hose clamps and a T-111 dummy header flange to maintain contact. In general, 6-inch long tube sections were used for experimentation, except for the preparation of mechanical test specimens, and in final trials to determine distortion effects from tube-to-tube welding of full length honeycomb tubes.

The welding torch size and selection of shielding gas were the initial considerations in the GTA tube-to-tube weld parameter study. For these internal welds, it was necessary that the torch be small enough to pass through the inside of the 0.850-inch OD by 0.010-inch wall T-111 tubes. The welding torch utilized in this investigation is shown in Figure 18. The maximum current carrying capacity was low for a torch of that size. That fact was of primary significance when considering the type of weld shielding gas, because the arc temperature would vary for an otherwise fixed set of parameters, dependent on the shielding gas present. Thus, during the initial GTA welding performed in a helium atmosphere, currents close to the maximum torch limiting value were necessary to achieve fusion of the tubes. Welding in an argon atmosphere would have required higher currents to produce equivalent joint characteristics. Further, the inert gas purification and chromatograph analysis systems for the welding chamber were set up primarily for helium usage. For these reasons, all GTA processing in this study was performed in helium, including tube-to-header welding and doubler indentations reinforcement.

Tungsten electrodes, 0.040-inch diameter, were employed in the tube-to-tube welding trials. After grinding to produce sharp conical tips, all electrodes were hot formed into the right angle configuration shown in Figure 18. To produce the most stable welding arc, the spacing between the electrode tip and the weld surfaces was set and maintained at 0.04 to 0.05 inch for most of the tube-to-tube joining. This spacing was reduced to 0.03 to 0.04 inch in tubes which contained EB attached doublers. The 0.03-inch clearance was considered the minimum point of approach to prevent possible extinguishing of welding arc, which could occur if excessive weld distortion were encountered.

Two, 4-tube bundle, sample assemblies were automatically GTA welded to explore primarily the effects of welding current and voltage. The tubes were cleaned for welding by acid pickling, in accordance with the previously indicated specification. The welds in these specimens were non-destructively inspected by visual (borescope), radiographic and ultrasonic techniques to measure not only their quality, but also to establish an acceptable method for subsequent inspection of hardware tube-to-tube welds, and to tentatively select the best welding power

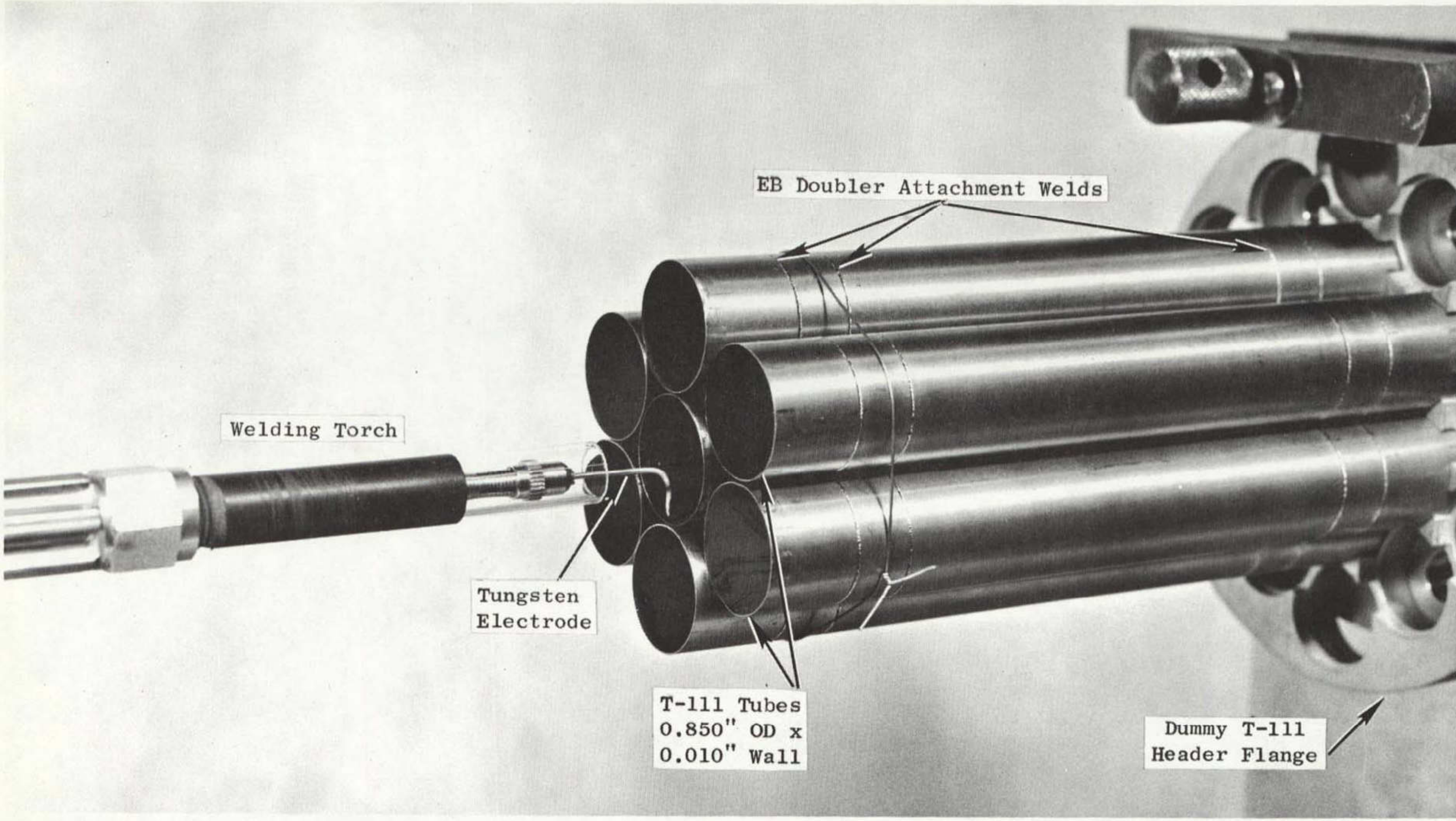



Figure 18. Closeup of Sample Tube Bundle and Special Welding Torch Ready for GTA Tube-to-Tube Welding. (70-6-13A)

input conditions. These tube bundles were then sectioned for microstructural examination to verify the selection of the optimum welding parameters.

## Mechanical Properties Test Specimens

At this juncture, three T-111 tube-to-tube specimens were GTA welded in preparation for mechanical properties testing. Each assembly was prepared from three sections of honeycomb tubing (three-inch-lengths), positioned such that their centerlines were located on the same axial plane. Two, one-inch long, welds were made to join the center tubes to the outer tubes of each specimen along their lines of mutual contact. The tubes were held in place for welding with the adaptors shown in Figure 19. These adaptors were subsequently used for conducting the shear tests on these specimens. The welding parameters of amperage, voltage, and speed were selected from the results of the previous parameter study specimen examinations. The completed tube-to-tube mechanical properties specimens are shown in Figure 20. The quality of the welds produced in these specimens was somewhat below that desired, because of a momentary lag between the start of welding and the start of motion of the assembly being welded. The result was the formation of circular weld spots at the start of the cycle, which had larger cross sectional dimensions than the remainder of the tube-to-tube welds. These specimens were considered satisfactory for mechanical properties testing, since the actual stresses carried by the axial tube-to-tube welds could be determined by comparisons of the weld cross sectional areas. Thus, the three samples were postweld vacuum annealed at 2400°F/1 hour, and subsequently tension tested at room temperature. The mechanical testing was performed in a Tinius-Olsen tensile machine; using a crosshead travel speed of 0.01-inch/minute.

## Tube-to-Tube Clearance Effects

Up to this point in the tube-to-tube welding investigation, effectively zero clearances between tubes had been maintained. This condition was believed to be a prerequisite for achieving sound welds. For the assembly of a full size tube-to-header honeycomb core support structure, the practical tolerance controls for tubing and header preparation

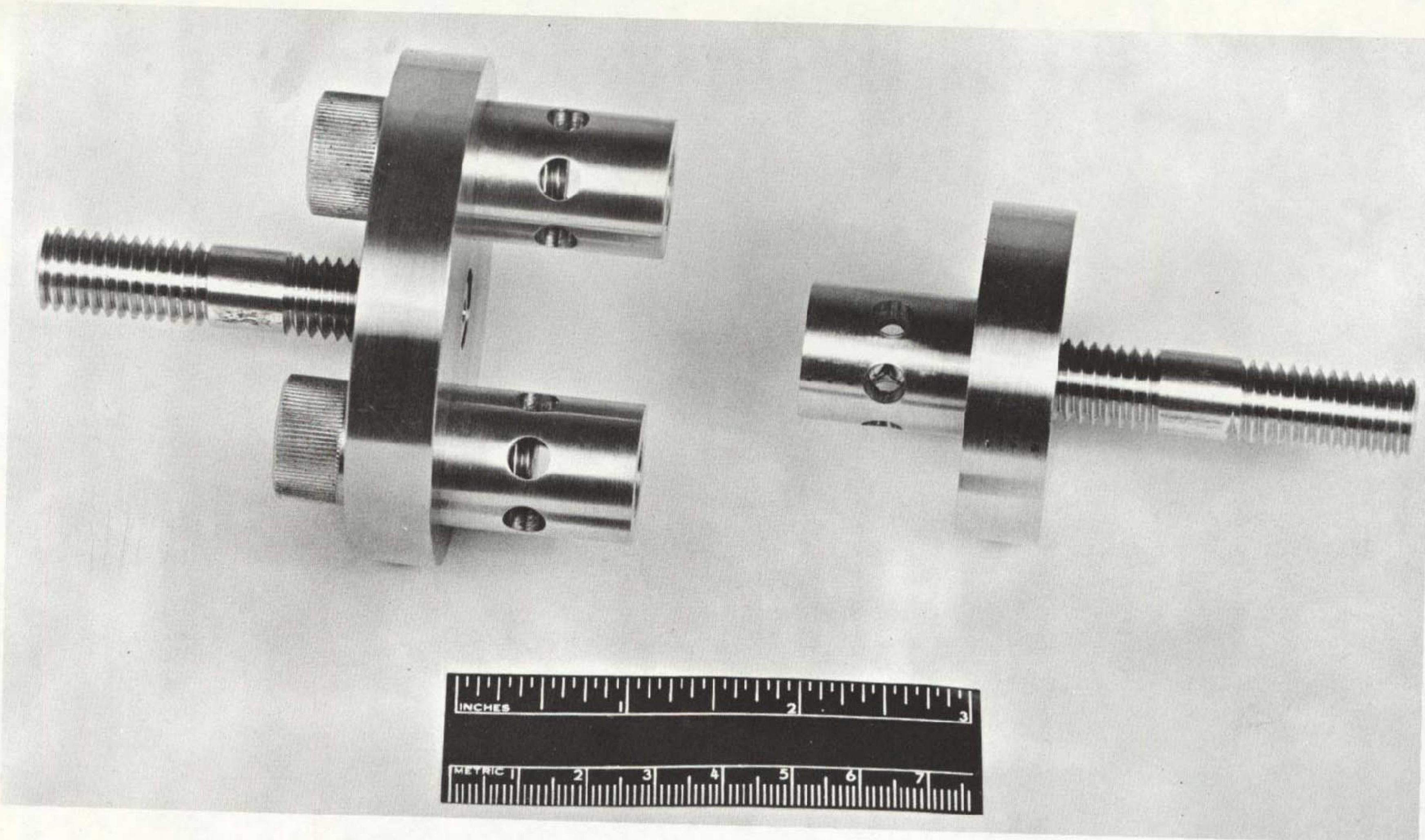



Figure 19. Stainless Steel Adaptors for Mechanical Testing of GTA Tube-to-Tube Weld Specimens. (70-1-9E)

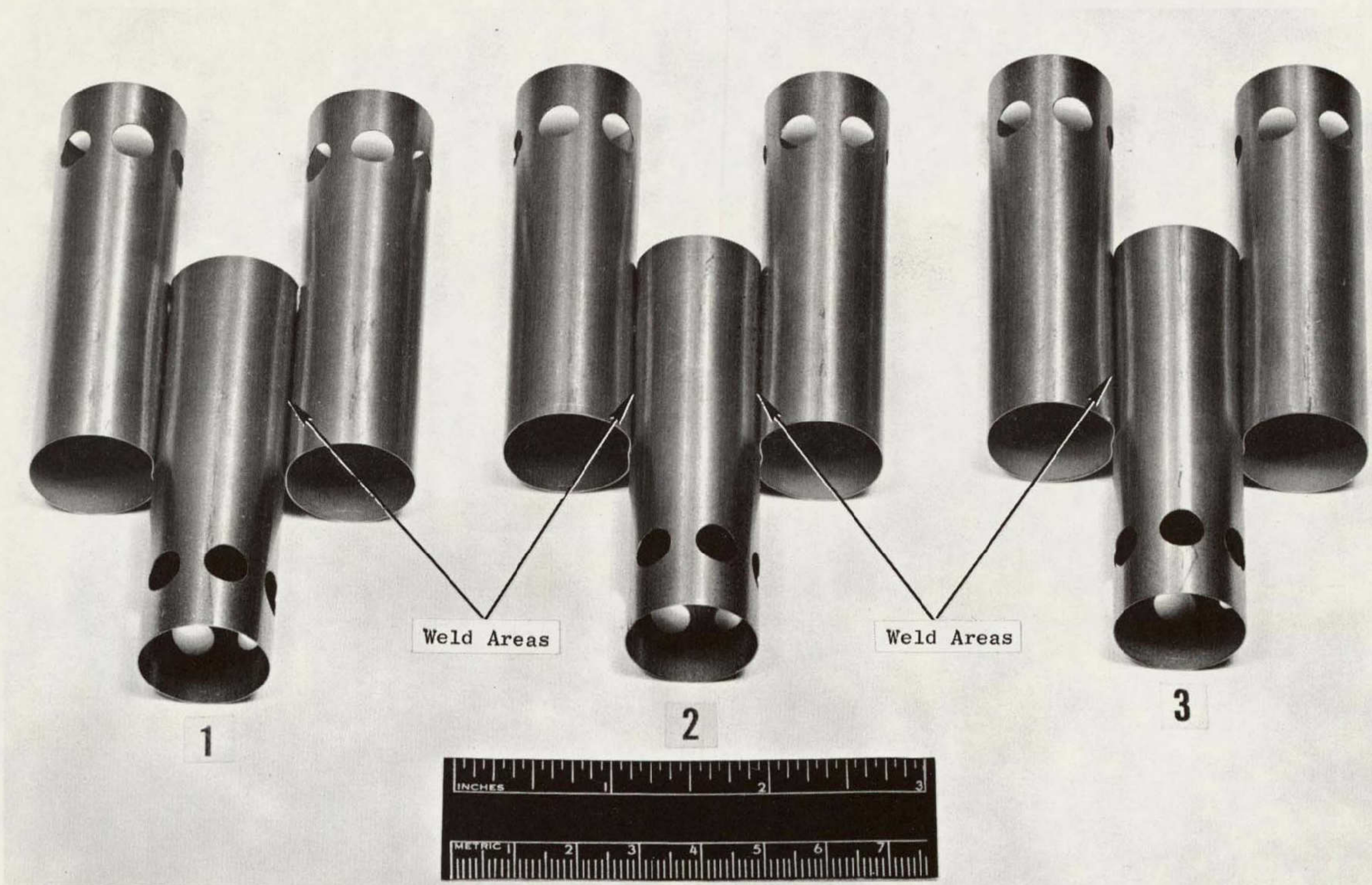



Figure 20. T-111 Tube-to-Tube GTA Weld Specimens for Mechanical Properties Testing - Before Test. (70-4-3A)

dictated that some greater clearance between tubes would be present. Therefore, a test was implemented to determine the maximum permissible spacing between tubes during welding. The test consisted of preparing a seven tube bundle, using six-inch-long, 0.850-inch OD by 0.010-inch wall, T-111 tube sections. The tubes were inserted in a T-111 core support header to provide the necessary support at their ends. That header was prepared such that the intertube clearance was zero immediately adjacent to its top surface. The configuration of the T-111 core support fixture is schematically shown in Figure 21. A 0.006-inch T-111 shim was then inserted between a tube pair at the unsupported end of the bundle to create a zero to 0.006-inch tapered clearance from end to end. A 0.020-inch diameter Cb-1Zr wire was used to hold the bundle at the end opposite the header, after the shim had been inserted. The seven tube bundle and core support header assembly was placed on the X-Y positioning fixture in preparation for welding, as shown in Figure 22. The internal automatic GTA welding of the tapered joint was initiated at the zero clearance end. The orientation of this joint in the seven tube array, and those of subsequent tube-to-tube joints prepared to study the effects of clearance variations on weldability, are shown in Figure 23. The welding parameters were adjusted, from those previously employed, to compensate primarily for the presence of the relatively massive end support header. The last tube-to-tube weld in this trial series was performed between two tubes, each containing two EB weld attached, indented and backfilled doubler inserts. Shims had been placed between the tubes at both ends, to maintain the maximum clearance which could be tolerated in GTA welding. The purposes of this test were to establish the effects of welding over doubler locations, and to produce a specimen for metallographic inspection to certify that the final GTA weld parameters were acceptable for joining tubes having relatively large separations. The metallographic sections were made 1) transverse through the GTA tube-to-tube weld, and 2) transverse through a doubler at a reinforced indentation site.

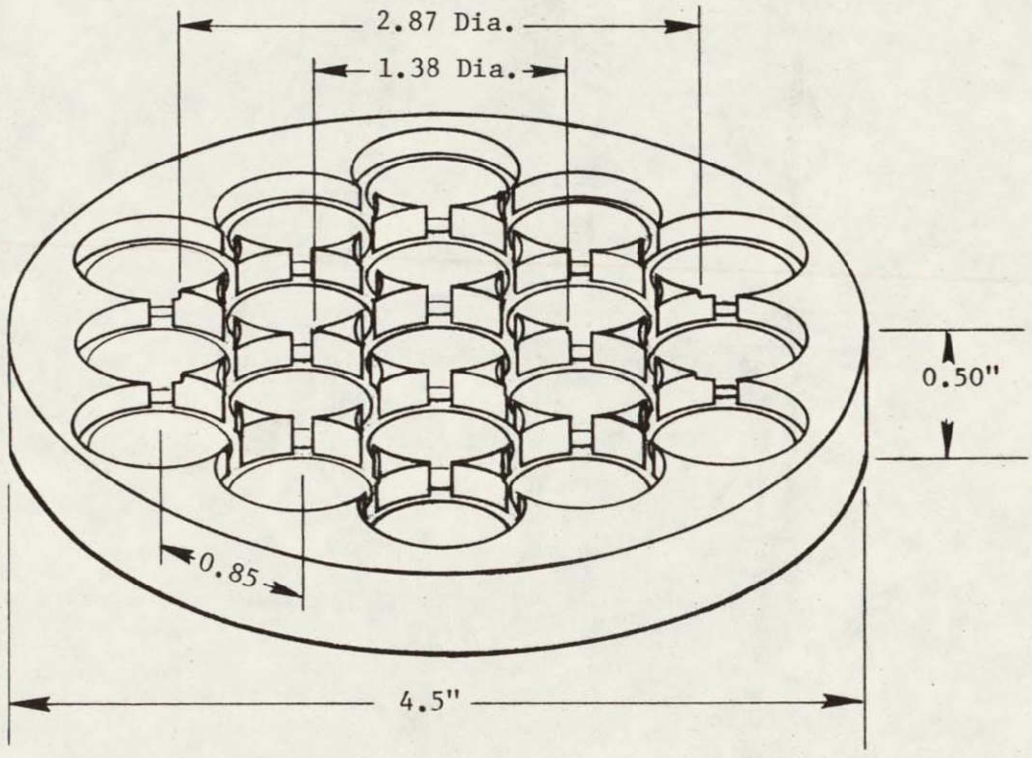



Figure 21. Sketch of the T-111 End Support Flange.

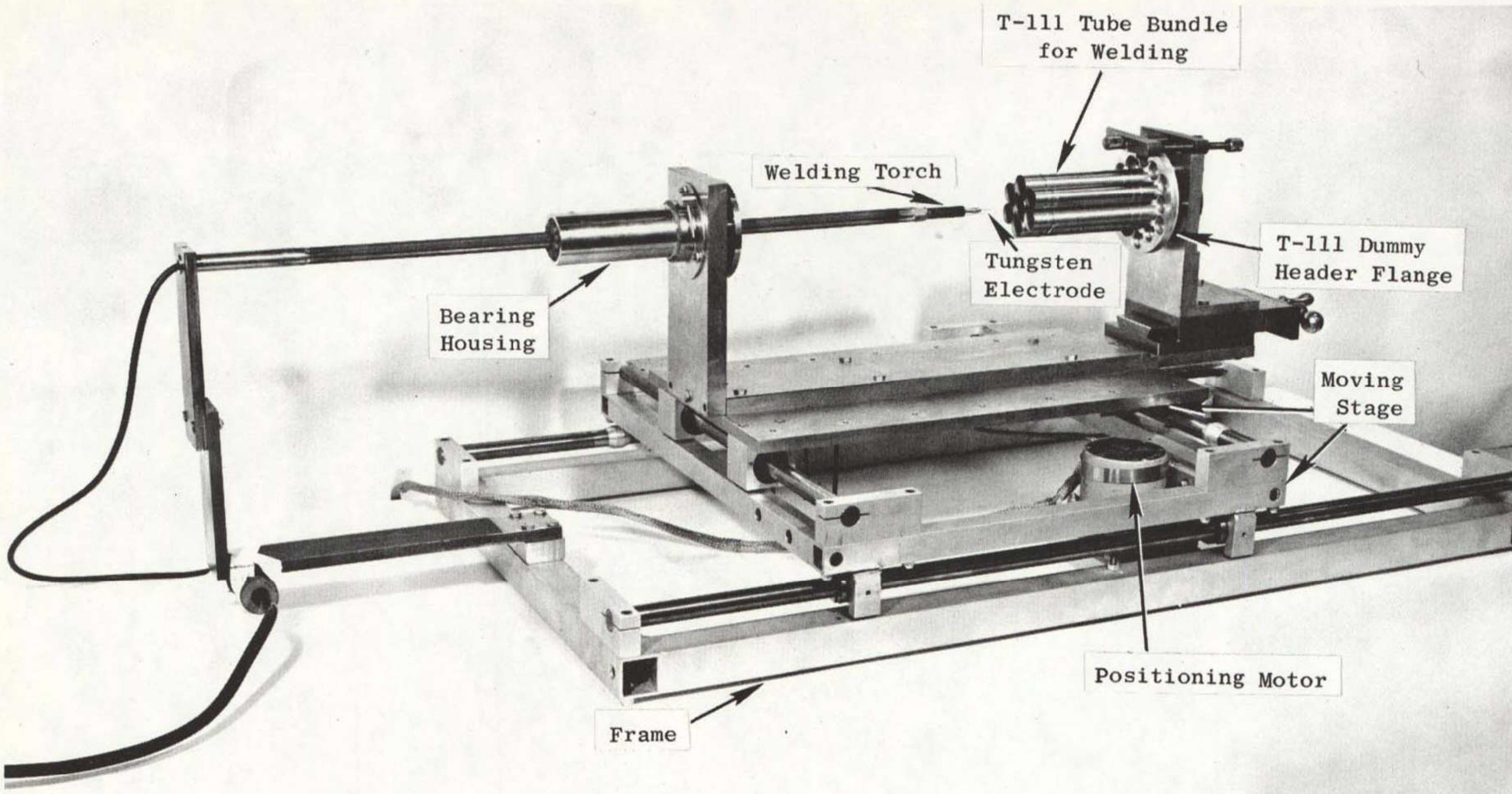
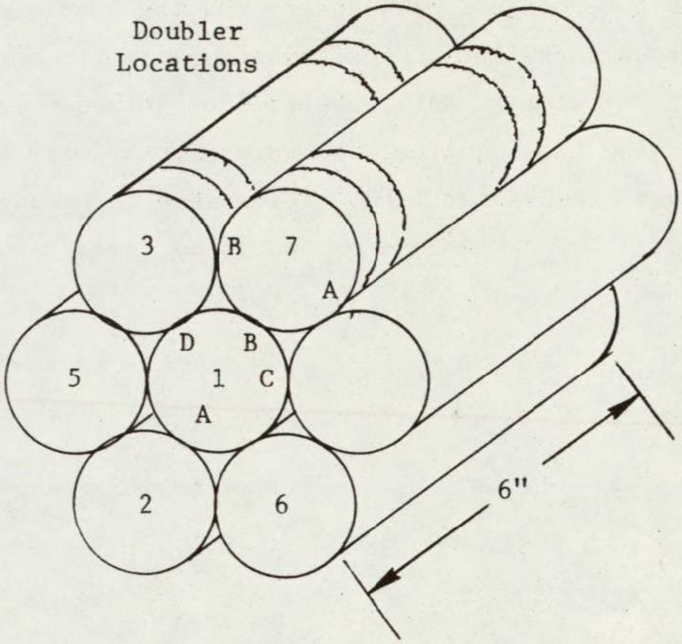



Figure 22. X - Y Positioning Fixture with Drive and Stationary Electrode for Producing Axial GTA Tube-to-Tube Welds. (70-6-13E)



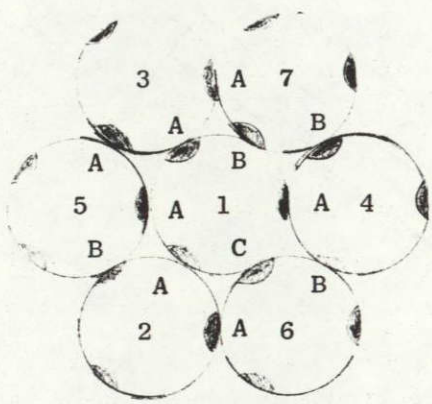

Identification (Typical): Weld 1A -Tungsten Electrode in Tube 1, Weld Made Between Tubes 1 and 2.

Tubes 5 and 6 Installed After Making Welds 1A and 1B.

Figure 23. Identification of Tube-to-Tube Welds in Seven Tube Bundle Sample Array.

Multiple Tube-to-Tube Welding Procedure

After the metallographic inspection of the above joint was completed, another seven tube bundle was prepared for welding. All tubes contained two dimpled and backfilled inserts, EB welded in place at the ends of the 6-inch-long tube sections. The assembly was prepared for welding in the manner anticipated for fabrication of a nineteen tube model honeycomb assembly. The tube-to-tube clearances, and the bundle width as a function of length, across three tubes whose axes were in the same plane, were measured prior to welding. All tube-to-tube joints were automatically GTA welded, making three center tube welds first, with the welding torch positioned inside the center tube. Welds were then made in each of the six outer tubes; i.e. either one or two welds in each tube as illustrated in the sketch below:




Weld Sequence: 1-A,B,C
2-A
3-A
4-A
5-A,B
6-A,B
7-A,B

The assembly was removed from the welding end support header , and inspected to determine distortion, shrinkage, and quality of the tube-to-tube welds.

The final experimentation in the tube-to-tube joining study consisted of welding a seven tube bundle, using full-length T-111 honeycomb tubes without doubler inserts. The fixturing for this assembly was different from that originally conceived for welding full-length tube bundles, primarily because no machined T-111 header flange was available for use as an end support. To best indicate the actual fixturing used, several comments will be made relative to the setup for welding a 19-tube-to-common header model assembly. For that assembly, opposite ends of the honeycomb tubes would be inserted into the model header flange

and the previously mentioned T-111 end support header, respectively. The welding torch would be inserted through a hole in a stainless steel indexing plate, and then through the support header for internal access to the tube-to-tube joints. The stainless steel plate with two attached cylindrical studs would be positioned immediately adjacent to the outside face of the end support header, such that the studs would penetrate to the mid-thickness of the flange. For the seven-tube array sample assembly, the torch guide, or indexing plate was modified and used to support one end of the bundle. The modification consisted of machining six additional studs to fit the inside diameter of the 0.850-inch-OD by 0.010-inch-wall T-111 tubes. Prior to assembly for welding, specific surfaces of the plate and studs, which contacted the tubes, were wrapped with protective tantalum foil. The opposite end of the bundle was supported by the end support header. Thus, the welding torch penetration for the full-length tube sample assembly was opposite to that for previous assemblies (refer to Figures 18 and 22). Twelve other full length honeycomb tubes were also positioned around the seven tube array to 1) produce a heat rejection or conduction condition in the seven tube array equivalent to that anticipated during welding of a nineteen tube model honeycomb structure, and 2) provide mid-length support for the interior tube cluster. Five equally spaced hose clamps around the outside of the 19-tube array were used to maintain contact of the tubes between the end support fixtures. To distribute the clamping forces, two-inch lengths of 0.25-inch-diameter molybdenum rod were inserted in the generally triangular zones formed by the inside clamp surfaces and the underlying tubes. Also, tantalum foil was wrapped around the bundle, under each hose clamp, to avoid possible damage or contamination of the outer T-111 tubes. The welding parameters utilized were those established as acceptable during earlier trials. The pattern or sequence of the welds was the same as that previously indicated for welding of the seven tube bundle, which contained EB attached doublers. The assembly was examined after welding to determine distortion effects and weld qualities, and to establish possible procedural variations which might improve the overall fabrication processing.

## Tube-to-Header Welding

The development of a method for bonding thin-walled T-111 tubes to a common T-111 header was explored using the internal, automatic, gas tungsten arc welding process. The process variables of welding heat input, electrode position and configuration, and rotational travel speed, were studied in conjunction with the design of simulated header components, to establish the conditions required to produce sound weldments. Postweld examination of trial specimens was used to select optimum parameters. All welding was conducted in a purified helium atmosphere in the previously described vacuum purge chamber, using a 0.062-inch-diameter bent tungsten electrode. Figure 24 presents a typical weld set up and depicts the position of the welding electrode in relation to a simulated header component. A potential arrangement for making tube-to-header welds in a multiple tube assembly is schematically shown in Figure 25. The rotating motor drive mechanism, torch mounting plate, and refractory metal (Cb-1Zr) support block actually used in the study are shown in Figures 26 and 27. Only single tube-to-header weld specimens were prepared in the investigation. Machined simulated header components and T-111 tube sections were cleaned for welding by acid pickling. The header components were machined such that the weld joints were self-fixturing, although a special tubing restraint fixture was used in later welding trials. The restraint fixture was used to a simulate conditions at the tube-to-header joints, which would be encountered in welding a multiple tube assembly after the tubes had been welded together. Visual (borescope) examination was the technique generally used to measure the relative quality of the welds. Metallographic examination of selected specimens was also employed to obtain more definitive analyses of the weld specimen characteristics, and thereby permit the selection of optimum preparatory conditions in subsequent specimens.

### Header Configuration Development

The first GTA welding trials for joining the 0.850-inch OD by 0.010-inch wall T-111 tubing to simulated T-111 header pieces were conducted ostensibly to determine only the weld power input and travel speed required to produce sound weldments. The configuration of the initial

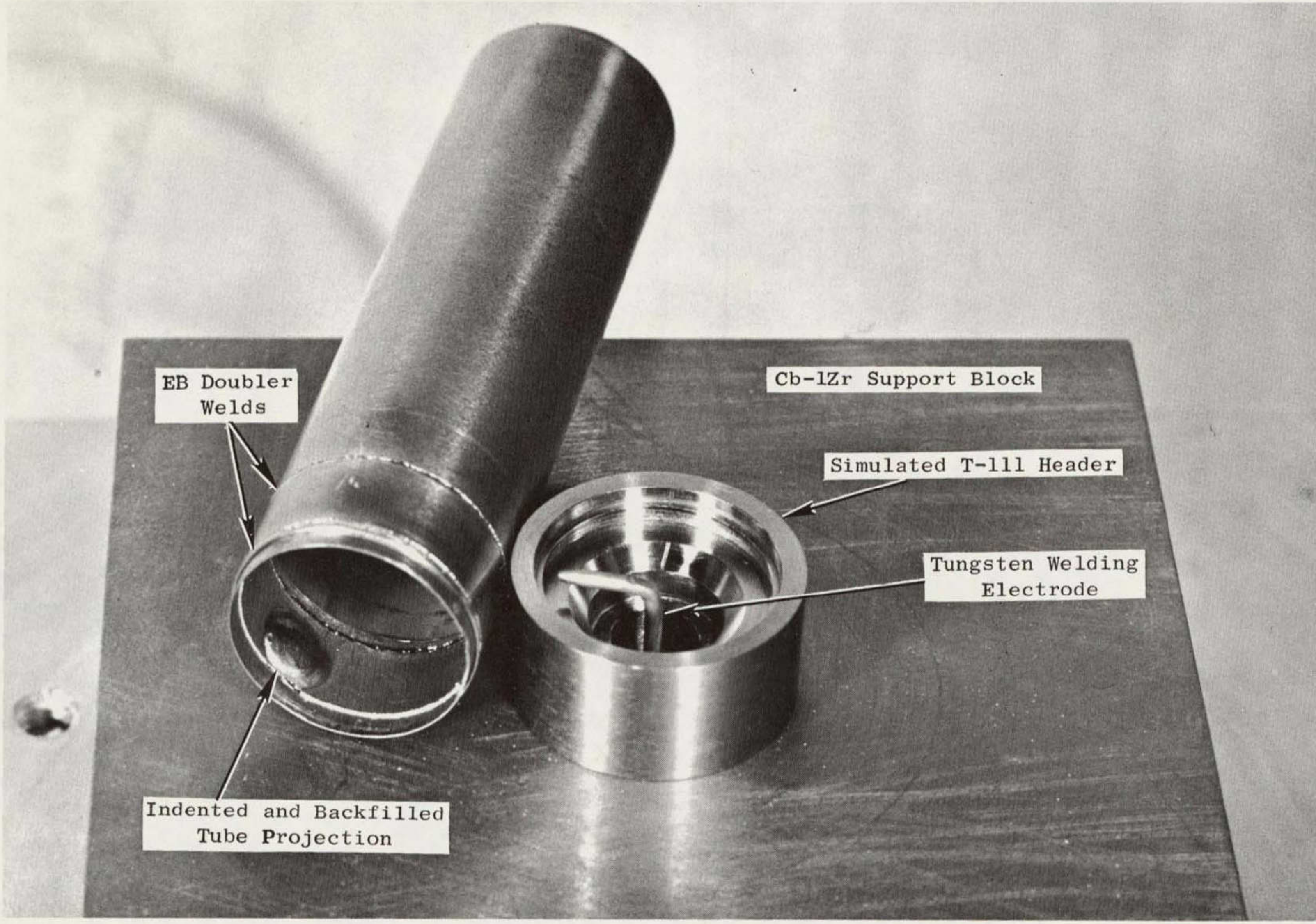



Figure 24. T-111 Tube with EB Attached Extended Doubler and T-111 Simulated Header Positioned Atop Cb-1Zr Support Block Prior to GTA Welding. (70-6-13B)

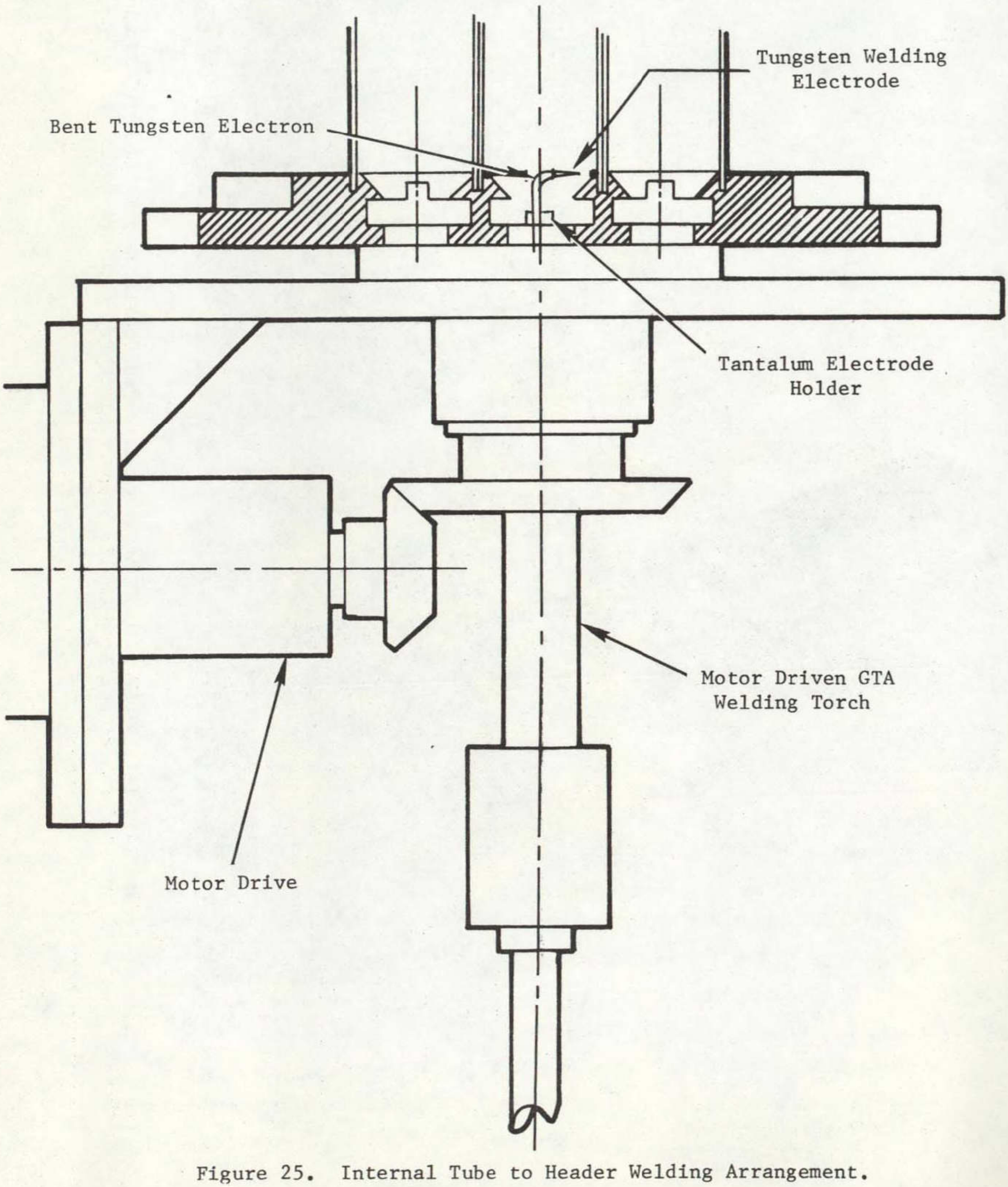



Figure 25. Internal Tube to Header Welding Arrangement.

2θ

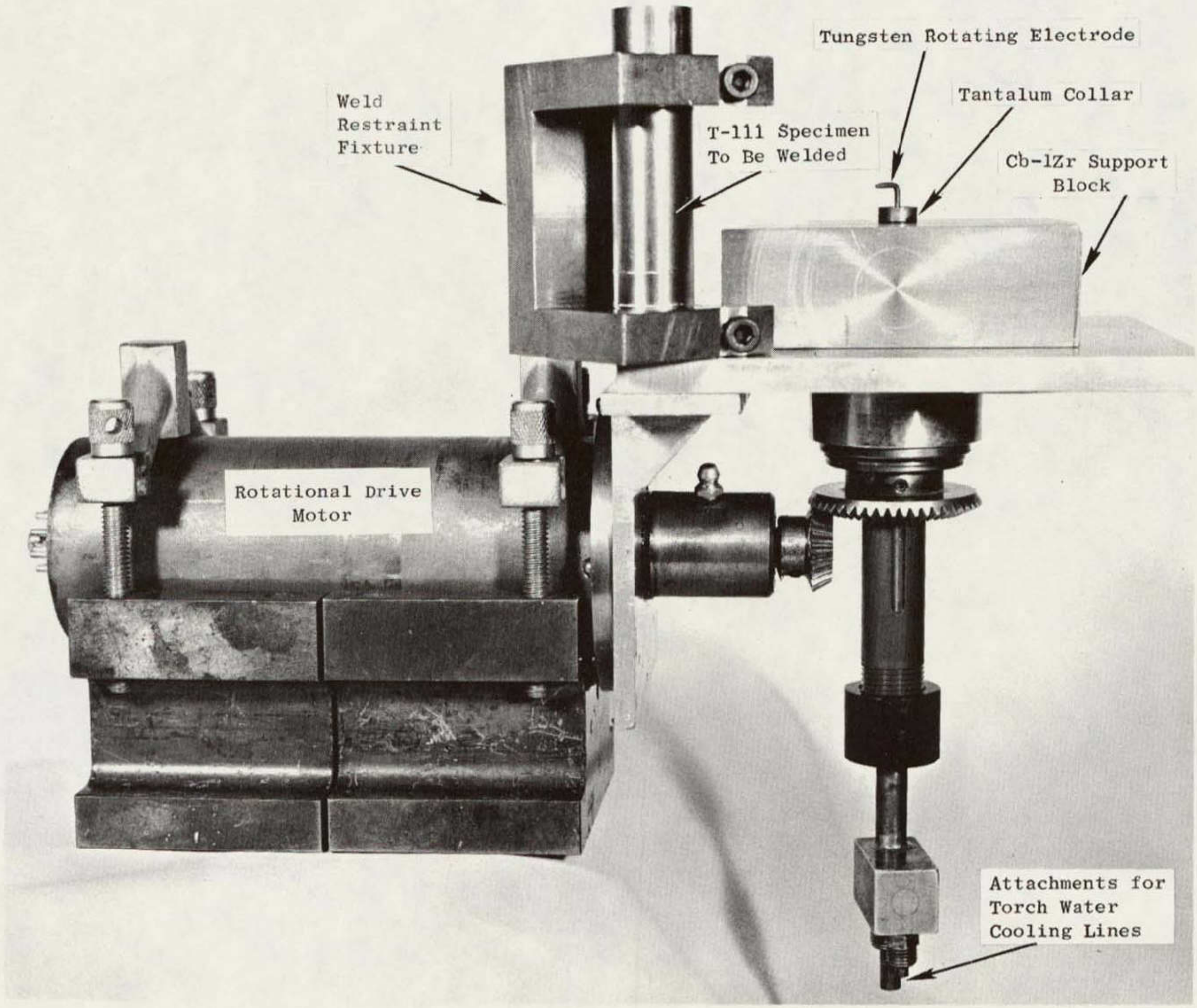



Figure 26. Tube-to-Header GTA Welding Setup with Drive Unit for Electrode Rotation-Before Positioning Specimen and Tantalum Restraint Fixture in Place for Welding. (70-6-13D)

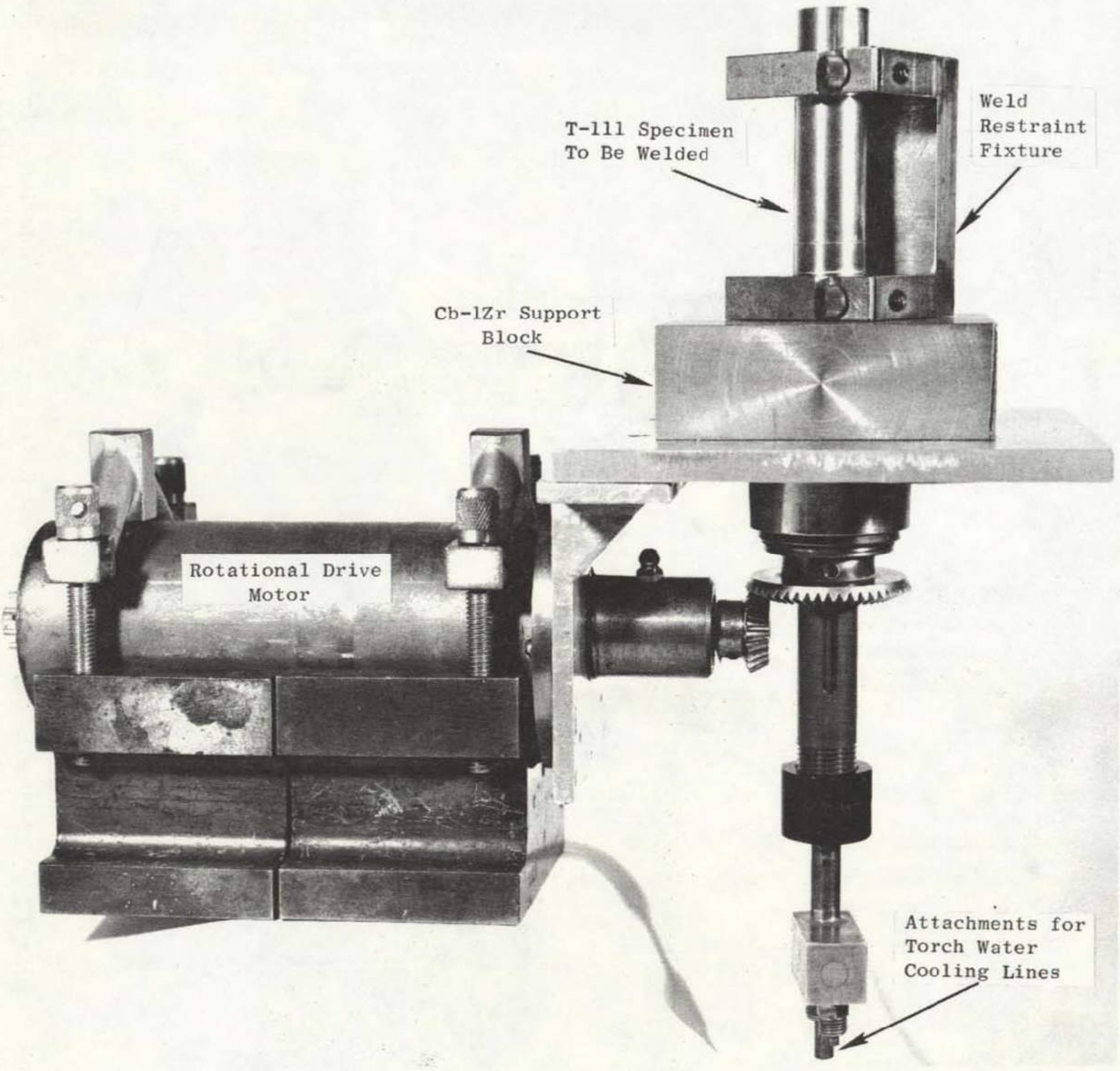



Figure 27. Tube-to-Header GTA Welding Setup with Drive Unit for Electrode Rotation-After Positioning Specimen and Tantalum Restraint Fixture in Place for Welding. (70-6-13C)

header pieces was identical with that portion of an originally conceived nineteen tube header flange where an individual honeycomb tube would be inserted; refer to Figure 2. Thus, the pieces contained 0.125-inch-deep circular slots for tube insertion, conical shaped sections with holes to simulate eventual lithium flow passages, and recessed rectangular slots. Because the welds in these initial specimens were unsatisfactory, additional header pieces were machined to remove material from the conical shaped sections immediately adjacent to the inside diameter of the tubing slots, as shown in Figure 28. The welds obtained from preparing specimens with this modified header configuration were partially acceptable. Metallographic examination of the last of these specimens indicated that further minor geometric changes would be economically and technically advantageous. Thus, four additional header pieces were machined to an alternate configuration; i.e., the slot depth was reduced to 0.08-inch, and the height of the rib at the inside of the slots was reduced by 0.015-inch to permit welding below the top surface of the header pieces. Subsequently, unsatisfactory joints were produced in the first two specimens, implying that some further processing changes were needed to protect the thin-walled T-111 tubes. Thus, the GTA welding of the remaining two specimens from the second group was attempted after doublers had been EB welded to the ID of the 0.850-inch OD tube, in such a manner that the base of each doubler and the top of the corresponding header ribs were in contact when the tubes were inserted in the header slots. The unsatisfactory nature of the resultant welds dictated that additional geometric alterations were needed.

Three simulated header pieces, containing slots for tube insertion, as shown in Figure 29, were machined for continuation of the tube-to-header welding investigation. The slots for these samples were machined to a depth of 0.140 inch using electrical discharge machining (EDM) techniques. Two of the header pieces were counter bored inside the ID of the slots to produce ribs having increased thicknesses (maximum possible thickness was 0.026 inch at the minimum counter bore diameter, 0.776 inch). The ID slot dimension for the third specimen was smaller than the other two specimens, such that the inside rib thickness was approximately 0.010-inch. Reduced diameter ring inserts were EB welded to the T-111 tube sections, such that the base of the inserts butted

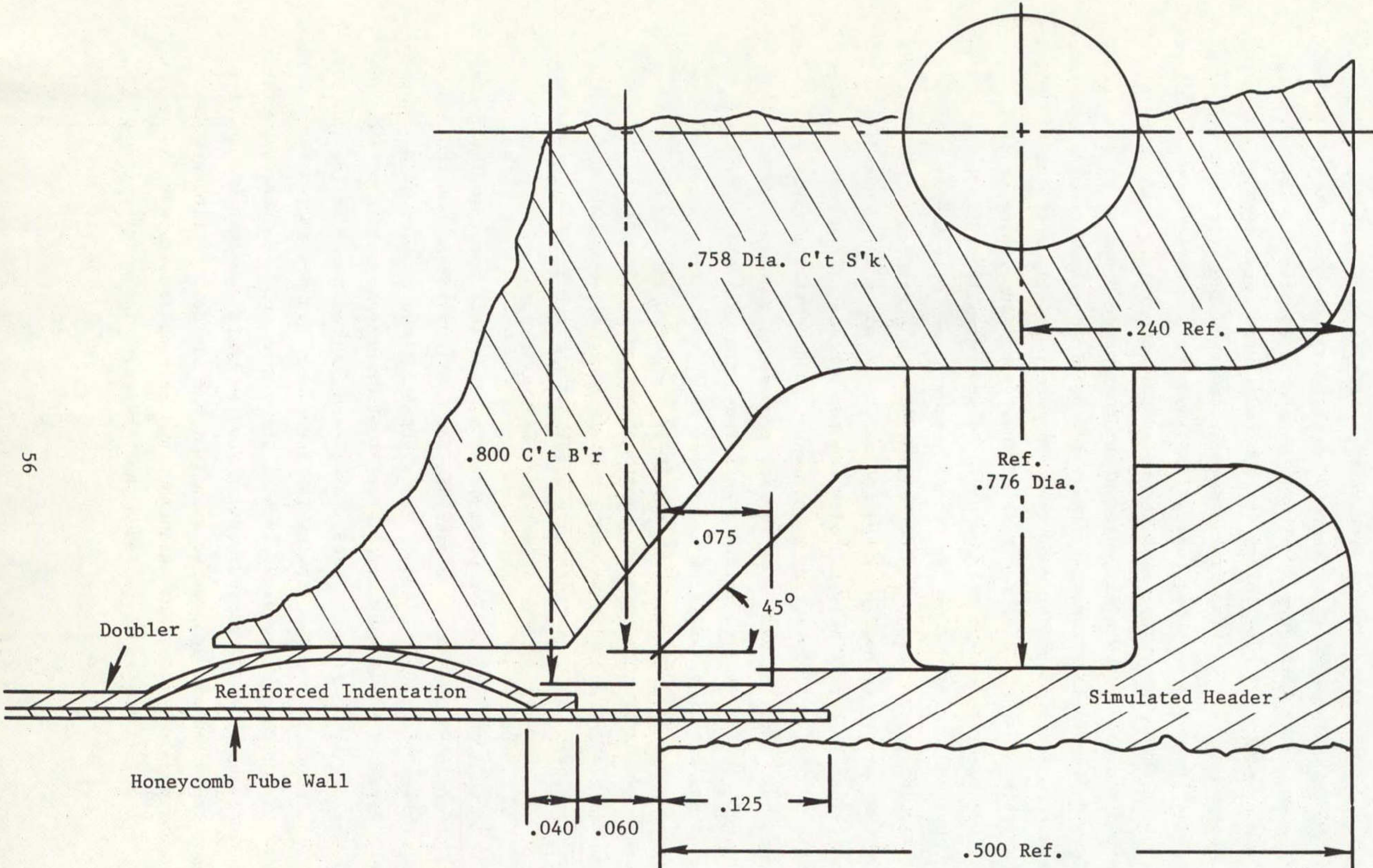



Figure 28. Detailed Dimensions of T-111 Simulated Header Components Prepared for Tube-to-Header GTA Welding Study (Interim Design Configuration).

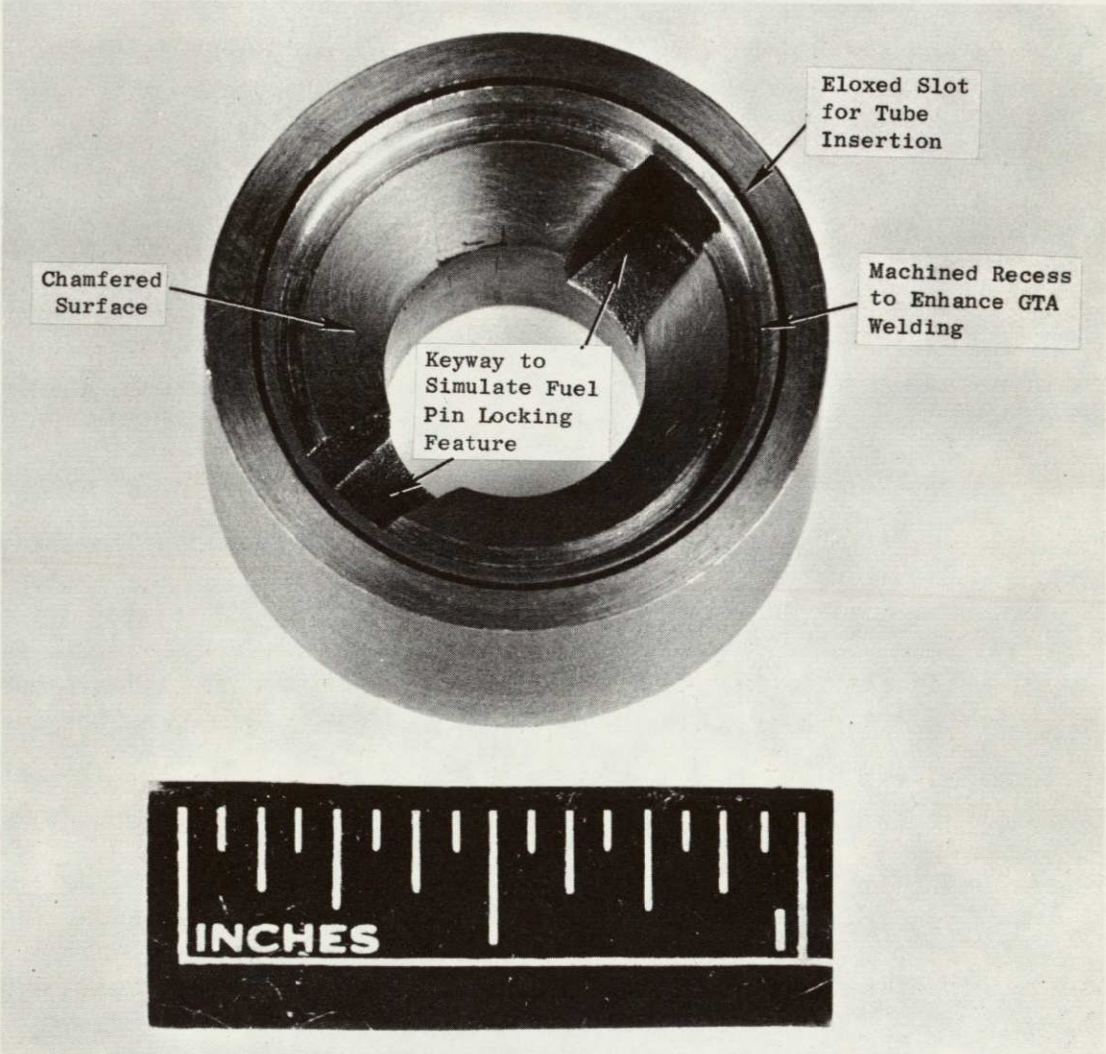
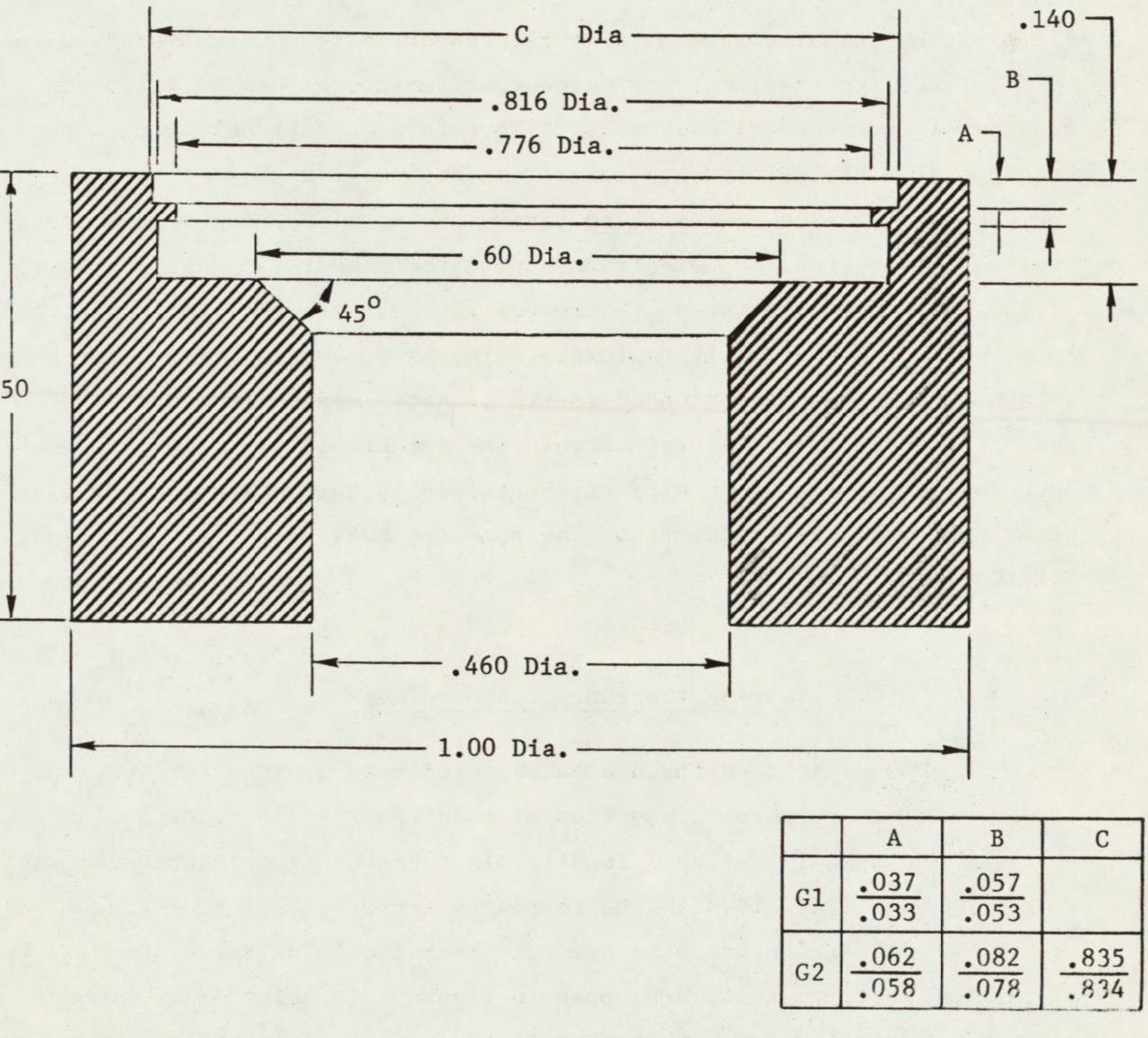



Figure 29. T-111 Simulated Header Piece for Tube-to-Header GTA Weld Parameter Study. (Refer to Figure 28 for Dimensional Details) (70-1-9A)

against the top of the internal slot ribs for the first two specimens, when the 0.85-inch-OD tubes were positioned for welding. The insert ring was located at the end of the tube for the third specimen, such that both the tube and ring were positioned inside the header slot before welding. The GTA welding of these three trial specimens was again unsatisfactory. These results were directly associated with the poor fitup of the tubes in the header slots.

Since the EDM process proved unsatisfactory for machining of the 0.140-inch-deep slots, a new sample header geometry was devised, which permitted the usage of more conventional machining techniques to produce the desired interior rib dimensions. The new configuration eliminated that portion of the header which formed the outside of the slots. Thus, the interior rib was above the main body of the header pieces. Three additional specimens were prepared for further GTA welding; diametric spacings between the ribs' OD and the tubes' ID were set at 0.005, 0.010, and 0.005 inch, respectively. Again, prior to GTA welding, reduced diameter ring inserts were EB welded to the tubing, such that the end of the inserts butted against the top of the ribs. The tungsten welding electrode was positioned 0.035 inch below the top of the rib for the samples with 0.005-inch diametric spacing, and 0.045 inch below for the sample with a 0.010-inch spacing. The welds produced were only partially acceptable indicating that a further variation in the tube-to-rib diametric clearance would be necessary to produce satisfactory welds.

Reducing the tube-to-rib diametric clearance to less than 0.005-inch appeared to provide a possible solution to the tube-to-header joining problem. However, such reductions were not compatible with tube bundling requirements in a multiple tube-to-common header honeycomb assembly, and a new approach was therefore considered. The result of that consideration was the tube-to-header joint configuration, shown in Figure 30. That design concept has three significant features; first, welds would be made between the header and an extended doubler insert; second, the clearance (0.005-inch), required for honeycomb assembly bundling, would be present between the insert OD and the header ID; and third, weld filler metal would be provided by the machined horizontal rib in the header.




| | A | B | C |
|---|---|---|---|
| G1 | .037 / .033 | .057 / .053 | |
| G2 | .062 / .058 | .082 / .078 | .835 / .834 |

Figure 30. Detailed Dimensions of T-111 Simulated Header Components Prepared for Tube-to-Header GTA Welding Study (Final Design Configuration).

Two trial samples were prepared to the configuration shown in Figure 30. The insert extension into the header (dimension A, Figure 30) was varied to be nominally 0.035 and 0.060 inch, respectively. In each case, the insert OD was measured and the respective header machined to provide a 0.005-inch diametral clearance. Welding trials were conducted using the restraining fixture to prevent tube motion in the axial direction during welding. Figures 31 and 27 show a schematic drawing and a photograph of the actual restraint fixture, respectively. Visual examination of the first two specimens indicated that further experimentation was required to produce reliable welds. Therefore, additional samples were prepared with the EB attached insert extension set at 0.06 inch into corresponding header pieces. The parameters of electrode tip shape, radial distance from the electrode tip to the header rib, axial position of the electrode relative to the header rib, as well as welding heat input, were systematically evaluated with these samples. The prior EB welding, to attach the extended length inserts, was performed without benefit of a welding fixture, because the expandable mandrel fixture had been fabricated for EB welding of short inserts only. The fixture was used to EB weld short inserts at the opposite ends of the tubes for wall reinforcement.

## Testing Procedure and Specimens

Holes were machined through these reinforced areas after tube-to-header welding, to permit insertion of load transmission pins during postweld mechanical testing. In all, six tube-to-header mechanical test specimens were GTA welded in the restraint fixture. All were vacuum heat treated at 2400°F for one hour prior to mechanical testing. Three of the specimens, prior to test, are shown in Figure 32. Selected specimens were also submitted for metallographic inspection to establish weld quality, and to determine whether parameter variations were required. The adaptors used for load transmission in the mechanical testing trials are depicted in Figure 33.

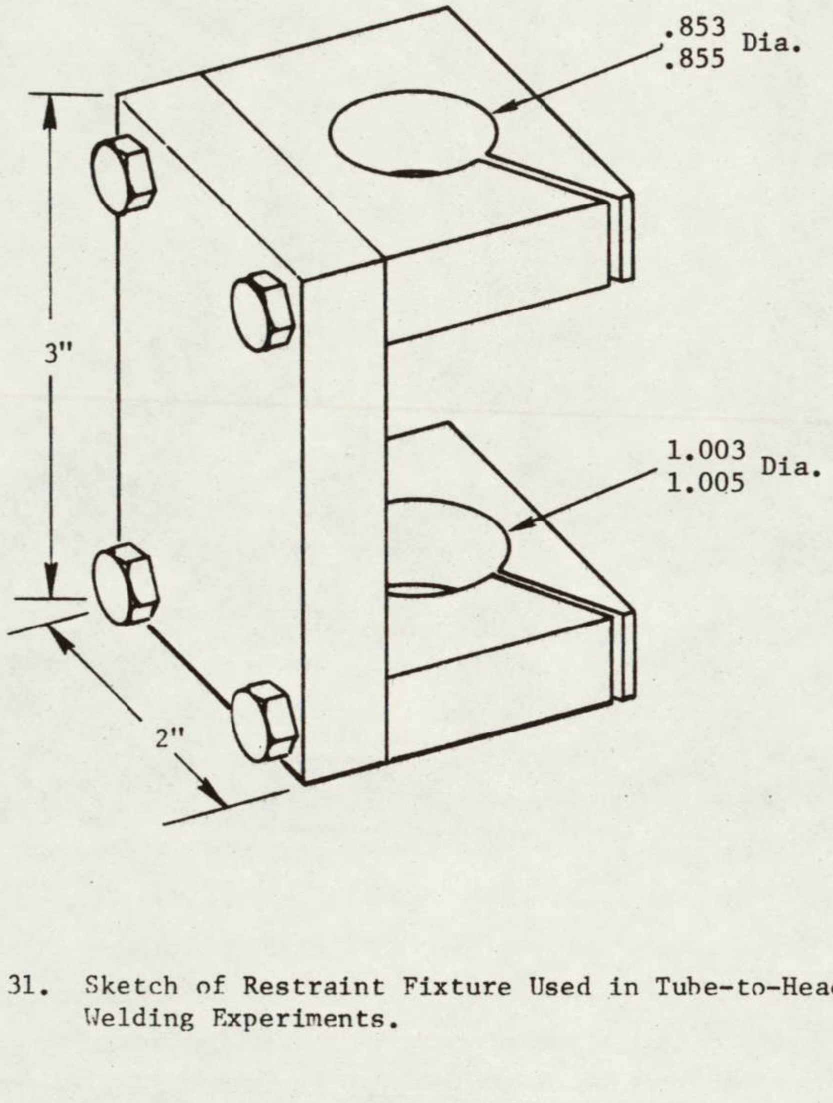



Figure 31. Sketch of Restraint Fixture Used in Tube-to-Header Welding Experiments.


Figure 32. T-111 Tube-to-Header Weld Specimens for Mechanical Properties Testing - Before Test. (70-8-7)

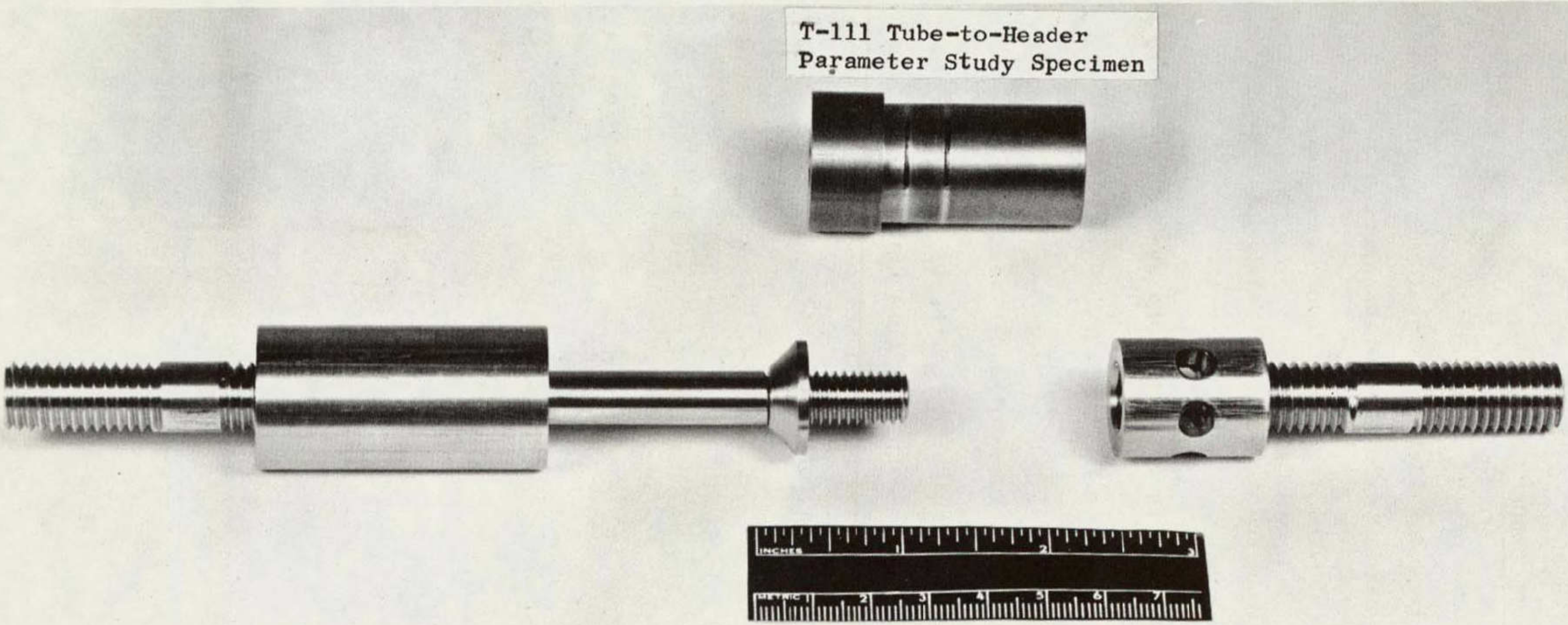



Figure 33. Stainless Steel Adaptors for Mechanical Testing of GTA Tube-to-Header Weld Specimens. (70-1-9D)

## SUMMARY OF PROGRAM PROCEDURES

During the course of the investigation of the honeycomb core support structure fabrication, detailed procedural plans were formulated and used for the following program experimentation areas:

1. Indenting and Reinforcing of Tubing Wall Doublers
2. Electron Beam Welding of Five Wall Doublers to a Full Length Honeycomb Tube
   a. Dimensional Inspection of Honeycomb Tube After Doublers Attachment
3. Gas Tungsten Arc Tube-to-Tube Welding
4. Gas Tungsten Arc Tube-to-Header Welding

In addition, a plan was generated for the EB welding of fuel pin retainer rings to a header flange. Joints of this nature would be encountered in the fabrication of a tube-to-header honeycomb assembly, as described later. The detailed plans for each of the proceeding areas are presented in the Appendix.

## III. RESULTS AND DISCUSSION

The basic purpose of the study program was to determine the feasibility of fabricating thin-walled T-111 alloy tubing into an integral honeycomb structure, for a potential nuclear power generating system application. The major tasks were the development of optimum techniques for producing (1) internal reinforced projections (fuel pin spacers) in thin-walled T-111 tubing, (2) welds between the T-111 tubes along mutual axial lines of contact, and (3) welds between the T-111 tubes and T-111 plate stock (simulated header components). These three fabrication areas were representative of portions of a proposed compact nuclear power plant. Thus, all processing and fixturing development was conducted with that assembly in mind. The three described fabrication areas were studied individually to generate reliable joining parameters, which would yield structurally sound trial assemblies exhibiting minimum distortion. Further aims of the program were to establish suitable postfabrication nondestructive inspection methods for determining the quality of the different joints, by comparing nondestructive and destructive (microstructural) examination data, and to certify that the developed parameters provided weldments, capable of withstanding applied mechanical stresses equivalent to those expected in service.

### FUEL PIN SPACERS FABRICATION AND WELDING

Experimental determination of the operating stresses in the honeycomb core of a proposed compact nuclear reactor indicated that reinforcement of the 0.875-inch-OD x 0.010-inch-wall tubing would be necessary

at the center fuel element alignment projections. That necessity initially appeared to complicate the situation regarding the manufacture of fuel element spacers. However, further consideration resulted in the evolvement of the dimpled insert, or wall doubler, approach for producing all of the spacers. As previously indicated, the advantage of the doubler method far outweighed the disadvantages, and it was therefore selected for evaluation. Reiterating, the three areas of investigation for producing fuel pin spacers by the wall doubler technique were (1) indenting of reduced-diameter T-111 ring inserts, (2) reinforcing the indentations with T-111 filler material, and (3) EB welding the prepared doublers to the wall of the basic T-111 honeycomb tubing.

## INDENTATION OF INSERTS

The most recent design configuration of a honeycomb core support structure indicated that the diametric variation to the nodal points of the internal tube projections ranged from 0.746 inch to 0.7625 inch. Two ways for achieving the different internal projection diameters were considered. Indenting inserts to the different depths prior to backfilling reinforcement was one candidate method. That technique would have necessitated the manufacture of at least two expensive indenting fixtures. The alternate, more economical, approach of indenting inserts to a fixed configuration, followed by backfilling on a water-cooled molybdenum fixture having machined recesses of different depths and contours, was devised and implemented to produce the desired projection diameters. The heat generated in backfilling caused the insert material to melt and conform to the fixture recesses, thus yielding the required internal spacer dimensions. Achieving the final spacer dimensions in prime hardware assemblies would require machining because the backfilling process is essentially a welding operation and compensation for the normal shrinkage attendant with that operation must therefore be made.

The required contour of the internal projections, shown in Figure 12, included a 0.295-inch-radius face. The previously described tube indenting fixture incorporated a 0.291-inch-radius ball for indenting the insert rings because the smaller size hardened balls were standard shelf items and could therefore be more easily procured. The desired quantities of T-111 ring inserts were indented, and subsequent dimensional

inspection of several formed pieces demonstrated that the required interim configuration had been successfully produced. Thereafter, backfilling of the doubler indentations with T-111 reinforcement material was explored by employing both the EB and GTA fusion processes for preparing samples.

## INDENTATION BACKFILLING

Radiographic and microscopic examination of the initial T-111 ring samples prepared by the electron beam process indicated several problems, which were cause for investigating the alternate GTA technique for backfilling the indentations. First, the surface contour of the solidified backing material did not meet the specified geometric requirements. The molten metal at the center of some indentations was attracted to the electron beam which produced an objectionable peak in the backfilled material when solidification occurred. Secondly, voids were detected at the bottom of several depressions, where the temperature had not reached a sufficient level to produce complete melting and flow. Overcoming this latter difficulty necessitated fusing a small portion of the required T-111 filler into the dimple cavity, then adding more material and repeating the cycle to achieve complete filling. This double cycle, coupled with the fact that each required evacuation of the welding chamber, were further reasons for rejecting the EB backfilling technique.

The GTA processing to backfill the doubler indentations was generally straightforward, and very few of the insert rings were rejected. Radiographic and dimensional inspection of a few inserts showed that the desired filling characteristics had been achieved. For a prime hardware assembly, each backfilled indentation should be radiographed to insure that filling was complete. Figures 34 and 35 display the contour and microstructures present at two typical indented and GTA reinforced doubler locations, both after the doublers had been attached to T-111 honeycomb tube sections in other program joining trials. As the figures demonstrate, excellent fill and flow were present. It was necessary to size all of the indented and backfilled inserts used in subsequent trials to study tube-to-tube, tube-to-header, and tube-insert-to-tube welding. The sizing was required because weld shrinkage effects from reinforcement had resulted in objectionable ring distortion which could not be tolerated during the following joining operations.

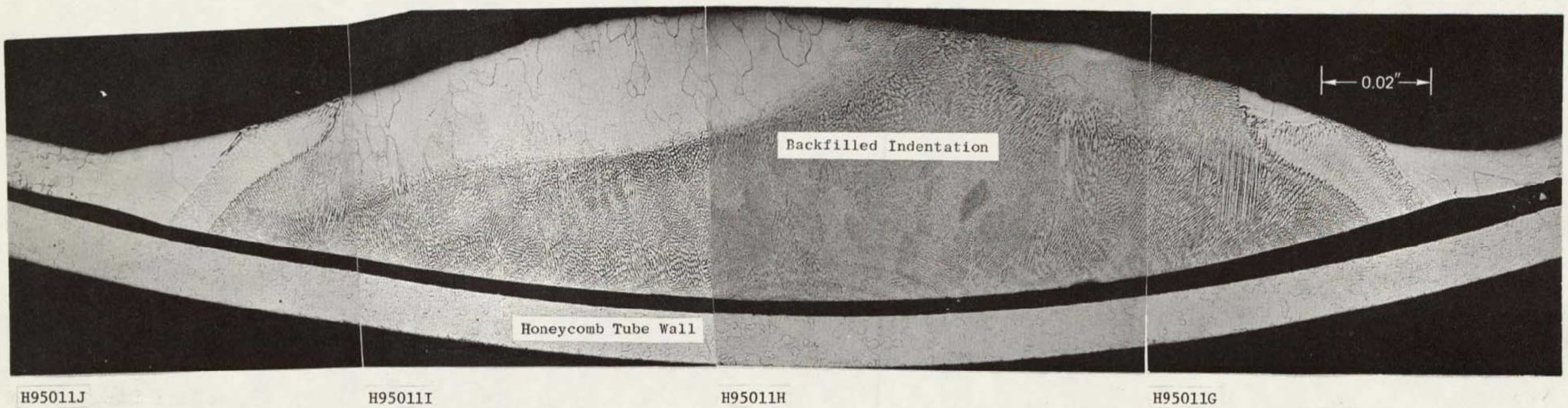



Figure 34. Microstructure of a Typical Backfilled Doubler Indentation Inside a T-111 Honeycomb Tube.
Etchant: $NH_4F$, $HNO_3$, $H_2O$

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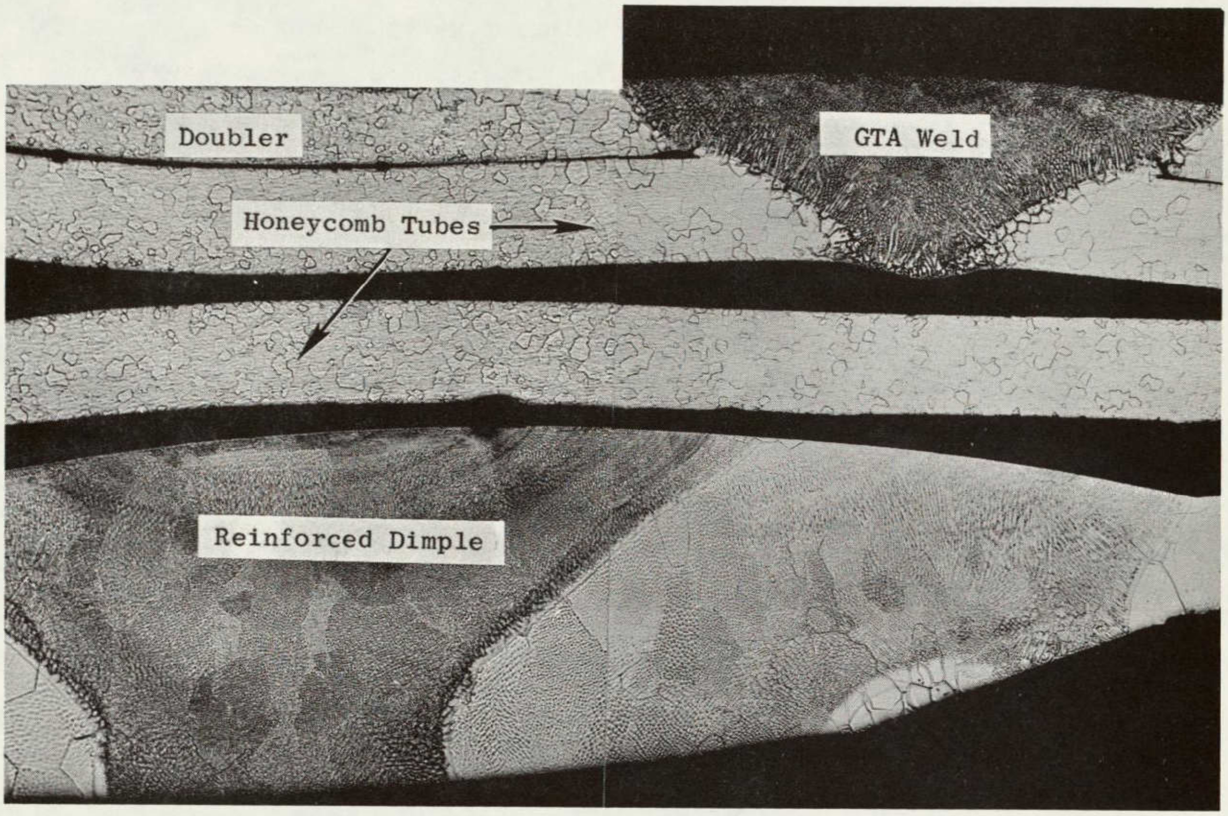
Tube-to-Tube Weld at Doubler Location

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Tube-to-Tube Weld at Mid-Length of Tube Pair

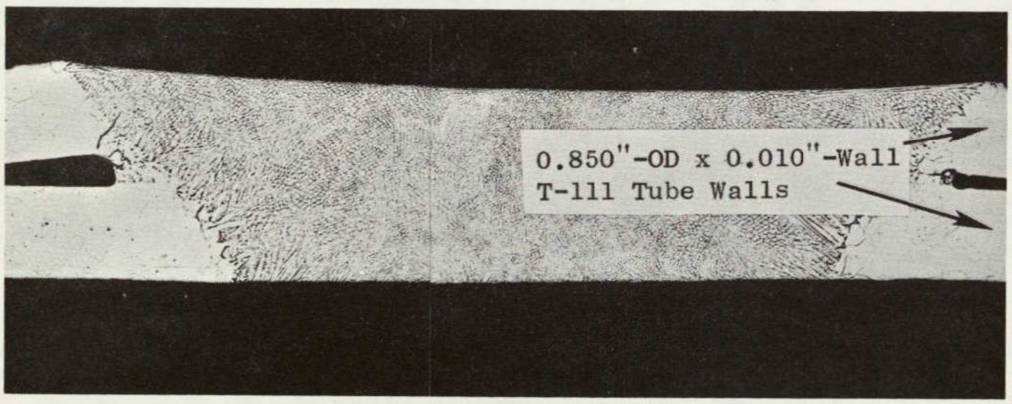


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Figure 35. Microstructures of Tube-to-Tube GTA Welded Assembly Transverse to GTA Weld Direction. Etchant: $NH_4F$, $HNO_3$, $H_2O$

## TUBE INSERTS-TO-TUBE EB WELDING

The development of a method for attaching the T-111 reduced diameter ring inserts or wall doublers to the wall of the basic T-111 honeycomb tubing entailed the high-voltage EB welding of various samples to establish optimum process conditions. Two types of attachment welds were required, i.e., circumferential welds around each doubler edge and "circular" welds around the doubler indentations. After the best processing conditions of fixturing, welding current and accelerating voltage, and welding speed were established from preliminary parameter studies, additional specimens were prepared to determine weld mechanical properties and distortion effects in a full-length (18 inches) honeycomb tube with five EB attached doublers.

### Circumferential Welding

The first EB welding trials were performed using single, 0.5-inch-long reduced diameter ring inserts without indentations. The rings were inserted into 3-inch lengths of the 0.850-inch-OD by 0.010-inch-wall T-111 tubing and circumferentially EB welded in place, using the parameters shown in Table II. An expanding, refractory metal, mandrel was utilized to maintain contact of the inserts with the tubing ID prior to welding. The welds were made immediately adjacent to the end of the fixture, over which the inserts were extended, to avoid bonding of the tubes to the fixture. Visual examination (10x) of these initial specimens indicated that satisfactory weld characteristics were associated with (1) particular welding variables and (2) maintaining sufficient diametric pressure to insure adequate contact of the inserts and basic tube wall. Thus, the EB welds around the circumference of the specimens were satisfactory only where the necessary contact had been maintained. Improvement of the contact could be more readily realized by reducing the rigidity of the insert rings. Two techniques were considered for achieving that goal; i.e., heat treatment of the inserts to remove stresses induced during tube reduction and axial splitting of the inserts. To check out the effectiveness of the first of these potential methods for enhancing the EB welding, several inserts were vacuum heat treated at 2400°F for 1 hour prior to their EB attachment in tube sections. Examination of the

TABLE II

RESULTS OF T-111 TUBE-INSERT-TO-BASIC-TUBE-WALL INITIAL EB WELDING PARAMETER STUDY

| | Welding Variables(1) | | | | |
|---|---|---|---|---|---|
| Joint Number | Beam Power (kv) | Beam Power (ma) | Welding Speed (Inch/Minute) | Target Height (Inches) | Remarks(2) |
| 1 | 90 | 2 | 58.5 | 0.25 | Penetration not established. |
| 2 | 90 | 4 | 58.5 | 0.25 | Penetration not established. |
| 3 | 100 | 5 | 58.5 | 0.5 | Variable penetration, target height changed to defocus beam. |
| 4 | 100 | 6 | 58.5 | 0.5 | 100 percent penetration, weld too large. |
| 5 | 100 | 4 | 58.5 | 0.25 | Beam power reduced to obtain smaller welds; target height changed to refocus beam, weld appearance excellent, penetration not established. |

(1) a. Welding performed using a Hamilton-Standard Company high voltage (6 kw) electron beam welder.

b. Welds were circumferential through the basic T-111 tube wall.

c. Target height = distance from focusing target to work piece.

(2) Observations based on visual examination of specimens.

samples, prepared by that technique, demonstrated essentially the same results as initially obtained. Thereafter, trials were conducted, utilizing split insert rings to improve the contact between them and the tubing wall. The results were again unsatisfactory. The electron beam, when moving over the split portion of the inserts, caused burn-through of the 0.85-inch-OD tube wall to occur, even though adjustments were made in the welding parameters, and the methods used to force the insert ends together.

Achieving the necessary contact between the inserts and the basic tube wall required an increase in the applied force, since reducing the rigidity of the inserts proved unsuccessful. Therefore, a second refractory metal, expanding mandrel, welding fixture identical with that to be used for doubler attachments in the full-length T-111 honeycomb tubes was prepared and utilized for the completion of the weld parameter study. The new fixture and adjustments in the initial welding parameters were utilized to minimize tube distortion and eliminate tube burnthrough. These additional trial welds were also the circumferential type. The results of the further parameter study, presented in Table III, show that minimum distortion was associated with complete penetration welds made using a sharp focused electron beam. The evaluation of those samples was based on visual examination of their exposed surfaces. On that basis, the following EB weld parameters were superior: accelerating voltage - 110 kv, beam current - 2.5 ma, rotational travel speed - 58.5 inches per minute. For quality assurance, additional samples were prepared using those parameters. Examination of these welds indicated that some alteration in the parameters might be beneficial for producing smoother weld contours. Thus, additional tube insert-to-tube samples were circumferentially EB welded using a wider range of process variables (including deflecting the beam parallel to the weld). Metallographic sections were prepared from pertinent parameter study specimens for a microstructural determination of the best welding conditions. The results of that determination will be discussed in a later paragraph.

## Circular Welding

Further EB welding trials were conducted to explore the circular EB weld attachments of indented and backfilled T-111 ring inserts to the ID

TABLE III

RESULTS OF ADDITIONAL EB WELDING PARAMETER STUDIES
FOR ATTACHMENT OF T-111 INSERTS TO BASIC T-111 TUBE WALL

| Joint Number | Welding Variables(1): Beam Power (kv) | Beam Power (ma) | Welding Speed (Inch/Minute) | Target Height (Inches) | Remarks(2) |
|---|---|---|---|---|---|
| 1 | 100 | 6.0 | 58.5 | 0.125 | Weld too wide, penetration not established. |
| 2 | 100 | 6.0 | 58.5 | 0 | Sharp focus produced narrow weld; partial through penetration; distortion not large. |
| 3 | 110 | 4.0 | 58.5 | 0 | 100 percent penetration, weld too hot, some tube distortion evidenced - weld power should be reduced. |
| 4 | 110 | 3.4 | 58.5 | 0 | 100 percent penetration, weld too hot, some tube distortion evidenced. |
| 5 | 121 | 2.0 | 58.5 | 0 | Power input too low, penetration not established. |
| 6 | 110 | 3.0 | 58.5 | 0 | 100 percent penetration, weld power slightly high, some tube distortion observed. |
| 7 | 110 | 2.5 | 58.5 | 0 | 100 percent penetration, optimum weld appearance - minimum tube distortion and through weld penetration. |

(1) a. Welding performed using a Hamilton-Standard Company high voltage (6 kw) electron beam welder.

b. Welds were circumferential through the basic T-111 tube wall.

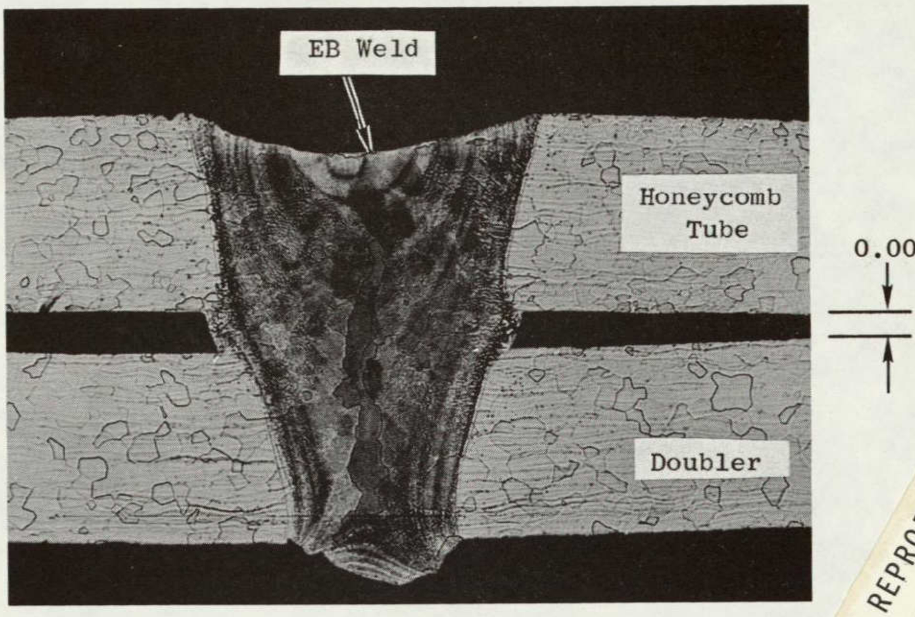
c. Target height = distance from focusing target to work piece.

(2) Observations based on visual examination of specimens.

of the honeycomb tubing. The range of welding parameters used in these trials was the same as that used in the study of circumferential EB weld attachments, and produced generally equivalent weld characteristics; i.e., the conditions which produced satisfactory circumferential welds also yielded satisfactory circular welds. However, the extent of distortion, associated with the circular welds, was somewhat greater than that experienced with circumferential welds, prepared under otherwise identical conditions. Selected circle weld parameter specimens were also submitted for microstructural study.

## Weld Microstructures

Representative microstructures from selected circumferential EB welds are presented in Figures 36, 37, and 38; typical circle EB weld microstructures are shown in Figure 39. Measurements of the weld dimensions and other pertinent comments for all parameter study specimens are presented in Table IV. The data show that the face and root dimensions changed from one location to another on the same specimen; i.e., considering the welds made at 110 kv - 2.5 ma, the weld face width varied from 0.018 to 0.022 inch, and the root width from 0.009 inch to 0.015 inch at the same respective positions (see Figure 36). These variations were possibly caused by changes in the power output, associated with slight fluctuations in beam current ($<$ 0.5 ma). Since low power levels were needed to join the thin-walled materials, current variations of that magnitude may have produced the observed effects on the size of the welds. Another plausible cause was associated with the variation in spacing between the tube and insert at the different positions. Thus, a larger separation resulted in a smaller weld cross section because the total volume of material present to solidify was effectively a constant. Weld dimensional changes of this magnitude were not considered detrimental from the standpoint of the structural requirements of a given EB attachment weld, regardless of the cause. A further observation from the microstructural study was that the face of the EB welds was depressed below the outside diametric surface of the honeycomb tube for certain specimens. This effect was quite pronounced in some cases, e.g., a depression of 0.007 inch was present in the sample welded at 90 kv - 5 ma (see Figure 37). The depressed portion of the weld was diametrically opposite to the starting location of the EB weld. Depressions were found at the face of the welds in most of the other specimens examined,

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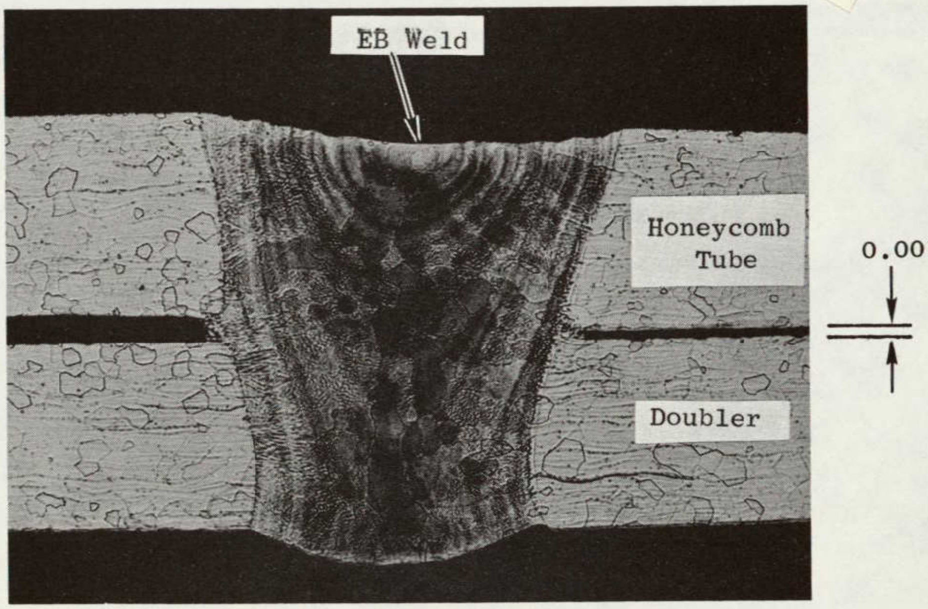


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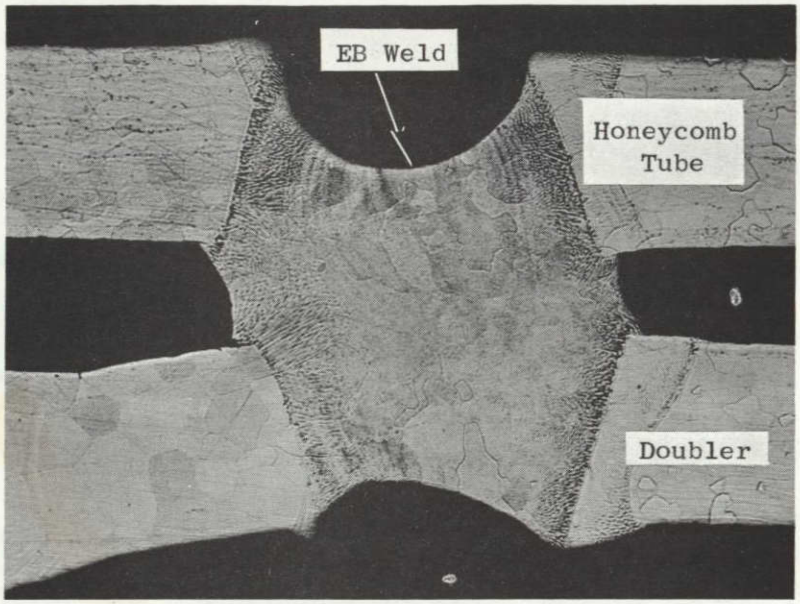
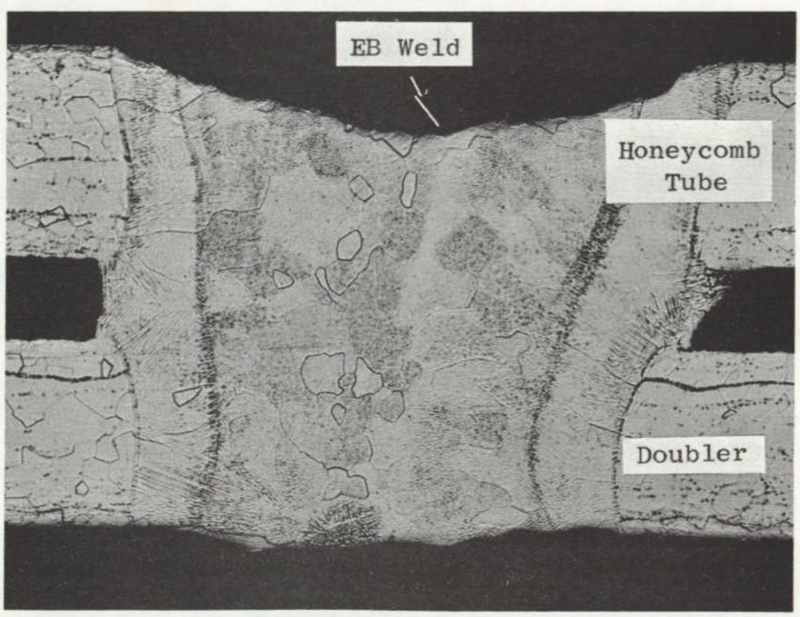
Figure 36. Microstructures of EB Welds (Circumferential) for Doublers Attachment Showing Effects of Slight Variations in Spacing Between Parts on Weld Fusion Zone Characteristics. Welding Parameters Were: 110 kv - 2.5 ma -No Beam Deflection. Etchant: $NH_4F$, $HNO_3$, $H_2O$




EB Weld Parameters:
90 kv - 5 ma - No
Beam Deflection

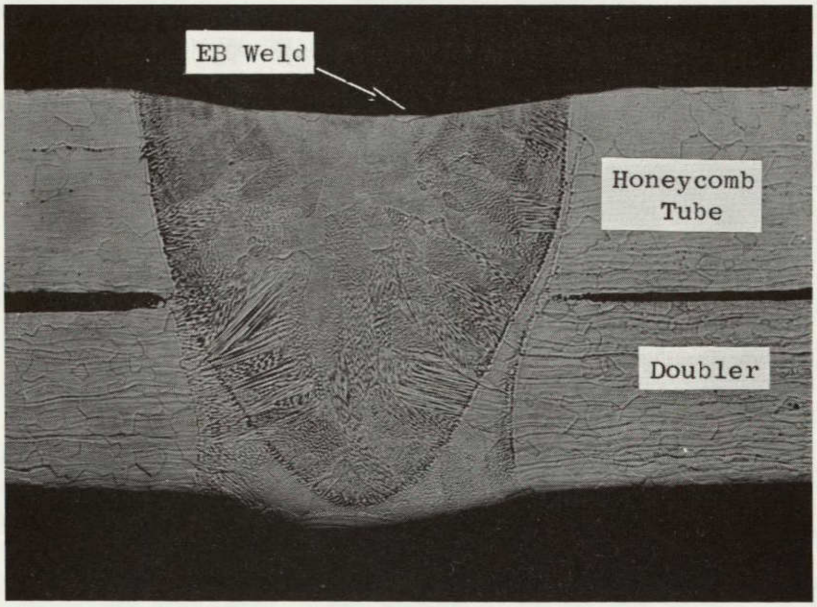
H70071A 100X




EB Weld Parameters:
120 kv - 4 ma - Beam
Deflection 0.05"
Perpendicular to
Weld

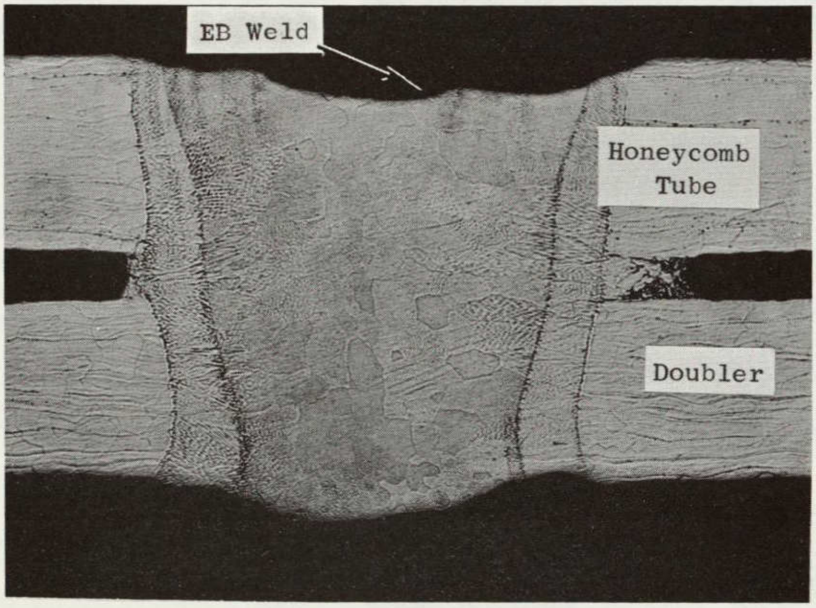
H70051A 100X

Figure 37. Microstructures of EB Welds (Circumferential) for Doublers Attachment Showing Effects of Relatively Large Spacing Between Parts on Weld Fusion Zone Characteristics. Etchant: $NH_4F$, $HNO_3$, $H_2O$




H70071B 100X

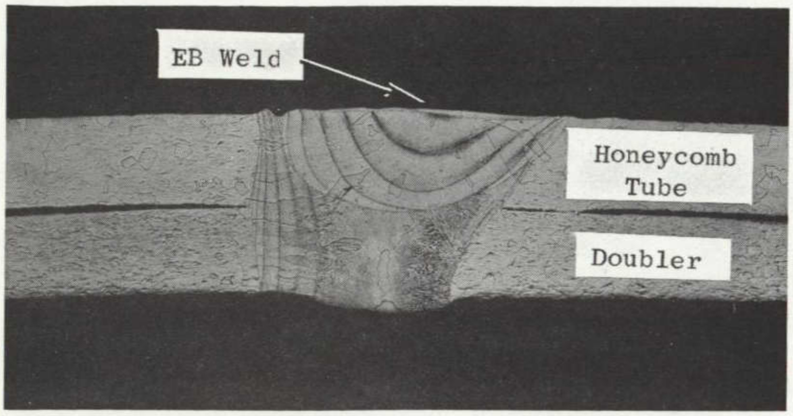
EB Weld Parameters:
90 kv - 5 ma - No Beam Deflection




H70071A 100X

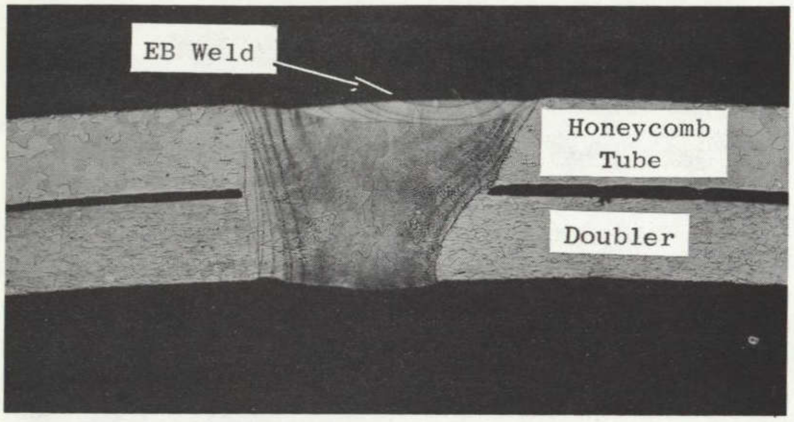
EB Weld Parameters:
90 kv - 5 ma - Beam Deflection 0.05" Perpendicular to Weld

Figure 38. Microstructures of EB Welds (Circumferential) for Doublers Attachment Showing Effects of Beam Deflection on Weld Surface Contour. Etchant: $NH_4F$, $HNO_3$, $H_2O$



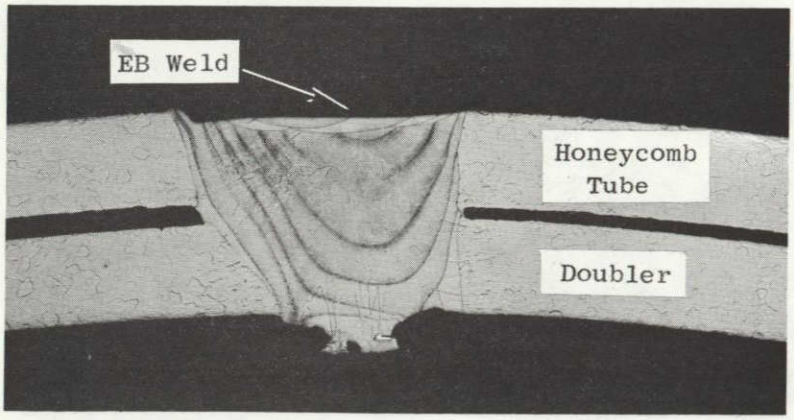

EB Weld Parameters:
90 kv - 5 ma - No
Beam Modulation

H95021B 50X




EB Weld Parameters:
110 kv - 4 ma - Beam
Modulation

H95021C 50X




EB Weld Parameters:
90 kv - 5 ma - Beam
Modulation

H95011A 50X

Figure 39. Typical Microstructures of T-111 Insert-to-Tube EB Welds Around Reinforced Indentations in Doubler (Circle Welds).
Etchant: $NH_4F$, $HNO_3$, $H_2O$

TABLE IV

DIMENSIONAL CHARACTERISTICS OF ELECTRON BEAM WELD FUSION ZONES FOR DOUBLER ATTACHMENTS

| Weld Number | Type of EB Weld | EB Welding Parameters: Power Input[1] (kv) | EB Welding Parameters: Power Input[1] (ma) | EB Welding Parameters: Beam Deflection[2] (Inch) | Spacing Between Doubler Insert and Honeycomb Tube Wall (Inch) | Weld Zone Dimensions: Face (Inch) | Weld Zone Dimensions: Root (Inch) | Weld Zone Dimensions: Depression[3] Face (Inch) | Weld Zone Dimensions: Depression[3] Root (Inch) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Circumferential | 90 | 3.0 | 0.05 | 0.0006 to 0.003 | ← Not Measured → | | | | Insufficient penetration. |
| 2a | Circumferential | 90 | 4.0 | 0.05 | 0.0012 | 0.022 | 0.016 | 0.0012 | --- | Full penetration, excellent weld appearance. |
| 2b | Circumferential | 90 | 4.0 | 0.05 | 0.0072 | 0.020 | 0.015 | 0.0054 | 0.002 | Wide spacing between insert and tube resulted in objectionable face and root side depression of solidified weld metal. |
| 3a | Circumferential | 90 | 5.0 | none | 0.0008 | 0.022 | 0.016 | 0.0012 | --- | Excellent weld characteristics observed. |
| 3b | Circumferential | 90 | 5.0 | none | 0.005 | 0.013 | 0.014 | 0.0068 | 0.0032 | Weld widest at midpoint between insert and tube; wide spacing again caused poor weld zone contour. |
| 4a | Circumferential | 90 | 5.0 | 0.05 | 0.0012 | 0.025 | 0.020 | 0.0016 | --- | Good weld; deflection of beam produced wider dimensions and rougher face contour. |
| 4b | Circumferential | 90 | 5.0 | 0.05 | 0.0024 | 0.026 | 0.022 | 0.002 | --- | Good weld; 0.0024-inch separation could be tolerated, 0.0015-inch distention observed on root side. |
| 5a | Circumferential | 110 | 2.5 | none | 0.001 | 0.022 | 0.015 | 0.0012 | --- | Good weld, although some root distention (~ 0.001-inch) evidenced; weld face contour smooth. |
| 5b | Circumferential | 110 | 2.5 | none | 0.002 | 0.018 | 0.009 | 0.002 | --- | Narrower weld resulted from slight power fluctuation; or space between components; 0.002-inch distention observed on root side; again smooth face contour. |
| 5c | Circumferential | 110 | 2.5 | none | 0.0015 | 0.019 | 0.012 | 0.001 | --- | 0.001-inch distention on root side, good weld. |
| 5d | Circumferential | 110 | 2.5 | none | 0.002 | 0.018 | 0.012 | 0.0015 | --- | Generally good weld. |
| 6a | Circumferential | 110 | 4.0 | 0.05 | 0.0048 | 0.020 | 0.016 | 0.004 | 0.0005 | Wide spacing (0.0048-inch) again resulted in large depression on face side, although less than with 90 kv beam voltage. Weld widest between insert and tube. |
| 6b | Circumferential | 110 | 4.0 | 0.05 | 0.002 | 0.022 | 0.021 | 0.0004 | --- | Weld zone exhibited least face-to-root taper. Depression in face side was not gradual as with other specimens. |
| 6c | Circumferential | 110 | 4.0 | 0.05 | 0.0032 | 0.019 | 0.019 | 0.0016 | --- | Root side of weld was smoothest of all specimens; results also indicated that 110 kv - 4 ma parameters were better when welding over relatively large spacing (0.0032-inch separation). Overall excellent welds. |
| 7 | Circumferential | 120 | 3.0 | 0.05 | 0.001 to 0.005 | ← Not Measured → | | | | Lack of penetration observed, effect caused by low heat flux density, related to improper beam focus adjustment. |
| 8a | Circumferential | 120 | 4.0 | 0.05 | 0.0016 | 0.030 | 0.026 | 0.002 | --- | Weld generally good, although face depression was sharp; dimensions largest observed. |
| 8b | Circumferential | 120 | 4.0 | 0.05 | 0.002 | 0.030 | 0.024 | 0.002 | --- | Approximate 0.002-inch distention noted on root side; again sharp demarcation in contour of face. |
| 8c | Circumferential | 120 | 4.0 | 0.05 | 0.006 | 0.030 | 0.026 | 0.004 | --- | Root side smooth, best parameters for welding over wide spaced tube and insert even though face depression was large (0.004-inch). |

TABLE IV (CONTINUED)

| Weld Number | Type of EB Weld | EB Welding Parameters: Power Input(1) (kv) | (ma) | Beam Deflection(2) (Inch) | Spacing Between Doubler Insert and Honeycomb Tube Wall (Inch) | Weld Zone Dimensions: Face (Inch) | Root (Inch) | Depression(3) Face (Inch) | Depression(3) Root (Inch) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Circular | 90 | 5.0 | none | 0.0001 | 0.034 | 0.020 | --- | --- | Face of weld smoothest observed; 0.002-inch distention noted on root side, larger fusion zone dimensions resulted from beam angulation; face-to-root shape not symmetrical. |
| 10a | Circular | 90 | 5.0 | 0.005 modulated | 0.0008 | 0.032 | 0.019 | --- | --- | Excellent weld, same as Specimen No. 9. |
| 10b | Circular | 90 | 5.0 | 0.005 modulated | 0.0002 | 0.036 | 0.022 | --- | --- | 0.0015-inch root side distention noted, otherwise good weld. |
| 11 | Circular | 110 | 2.5 | none | 0.0002 to 0.0014 | ← Not Measured → | | | | Lack of penetration observed, travel speed was too rapid for fusion to occur. |
| 12 | Circular | 110 | 3.0 | 0.005 modulated | 0.0001 to 0.0008 | 0.044 | Not Measured → | | | Lack of penetration, beam focus out of adjustment. |
| 13 | Circular | 110 | 4.0 | 0.005 modulated | 0.0015 | 0.035 | 0.02 | 0.002 | --- | Full penetration observed; face depression was sharp variation from tube contour; 0.003-inch distention of weld noted on root side; root contour very poor; weld not symmetrical. |
| 14 | Circular | 120 | 4.0 | 0.005 modulated | Not Measured | ← Not Measured → | | | | Extremely poor contour on both face and root sides. |

NOTE: (1) Weld Travel Speed Was 58.5 inch/minute for all Trials.

(2) Deflections Indicated Were Parallel to Weld Path.

(3) Depressions in Weld Fusion Zones Were Measured at Maximum Depths.

but to a lesser degree. The root sides of the fusion zones in some specimens were also recessed, whereas others were distended. The magnitude of the face and root contour variations was directly related to the separation between the tube and doubler at the particular site; thus, a larger separation resulted in a greater contour change in the weld fusion zone. The separation was attributed to an initially poor fitup between the parts. At the start of welding, the two components were pulled together at one point, which thereby forced any initial radial clearance between them to be gathered at a diametrically opposite position. The basic difficulty was that the tolerances on the honeycomb tubing, and the variation in doubler diameters, could result in large clearances at assembly (up to 0.006 inch). For the preparation of subsequent honeycomb tubes and inserts for EB welding, sufficient force was exerted on the expandable mandrel to cause upsetting of the inserts, thus causing them to conform to the ID of the honeycomb tube and also produce the necessary intimate contact.

Deflection of the electron beam parallel to the weld path was utilized to determine whether the surface texture of the weld zone could be enhanced. As shown in Figure 39, such beam deflection actually produced an undesirable rippling effect on the circumferential weld surfaces. Beam modulation during circle welding at 90 kv - 5 ma also detracted from the weld appearance, also shown in Figure 39. That figure also displays the circular weld made at 110 kv - 4 ma, with beam modulation, which had the worst root side contour of any weld inspected. Beam modulation refers to the dilating and contracting of the circular electron beam while tracing the weld pattern.

Microstructural examination of the circular weld made at 110 kv - 2.5 ma showed insufficient penetration. The electron beam rotation was fixed at 60 cycles per minute for all circular weld parameter trials. The diameter of the circular weld path was greater than 0.31 inch for that specimen. Since a constant rotational beam motion was maintained, the linear weld travel rate for that specimen exceeded that employed in producing the circumferential welds (58.5 inches/minute). Thus, the unit heat flux on the surface of the above indicated specimen was too low to produce complete fusion.

Incipient melting was noted in the T-111 grain boundaries next to the weld fusion zones (heat-affected zones) of some specimens. With that exception, all welds examined were satisfactory from a metallurgical standpoint; i.e., no porosity, grain boundary separation or other anomalies were detected. A further conclusion of the microstructural study was that visual examination of the face and root of a given EB weld could satisfactorily define its acceptability.

## Optimum Weld Conditions

Based on the microstructural study of the EB welded parameter specimens, several parameter combinations could be potentially used to produce metallurgically sound, complete penetration welds. For that reason, the selection of the optimum welding conditions for attaching doublers was based on the following factors:

1. The extent of assembly distortion;
2. The contour of the welds;
3. The relative reliability of the welding operation.

Increasing the EB welding power and the corresponding heat generated, normally results in greater assembly distortion. From that consideration, the parameters of 110 kv - 2.5 ma were superior, although the observed effects in the actual specimens was slight. The beam accelerating voltage has the most significant effect on the weld geometry; i.e., decreasing the voltage produces smoother but wider welds. Visual examination of the parameter study specimen's outer weld surfaces indicated that this effect warranted more consideration than the assembly distortion. The surface texture of the welds, prepared at 90 kv - 5 ma, was much superior to that obtained by using other variables. The wider welds, attendant with the lower voltage - higher amperage condition, were considered advantageous, because greater transverse shear stresses could be tolerated in service.

Variations in accelerating voltage have a more pronounced effect on the electron beam characteristics than a proportional change in any other parameter. A minor fluctuation in voltage at higher levels would be more deleterious than the same variation at lower levels. Thus, the parameters of 90 kv - 5 ma represent the most reliable combination for EB welding of doublers. Since superior geometries were also associated with welding

at that power level and distortion effects slight, those parameters were selected for subsequent program usage. The validity of the selection was verified by the preparation and examination of multiple insert-to-tube specimens.

## Tests of Load Carrying Capacity

The testing to determine and qualify the shear load carrying capability of the EB doubler welds was conducted at room temperature, using specimens fabricated from three-inch-long sections of reduced diameter tubing and basic 0.850-inch-OD tubes. Three specimens were tested - two each having three circle welds, and the third, a single continuous circumferential weld. As indicated previously, the most critical of the EB doubler welds in the final nuclear power plant core structure are those around the fuel pin retainer located at the mid-point of the tube. The radial force from the fuel elements on the honeycomb tube internal protrusions during service would impose shear stresses on those circle welds. Further, axial stresses across those welds would be encountered during launch. Thus, the testing of the indicated EB weld samples, by the application of axial loads, provided qualitative strength date pertinent to the launch requirements, and also yielded a quantitative measure of the weld shear strength. No weld failures were observed in any specimen under applied loads to 1000 pounds (failure occurred through the pinholes of the tubing at the indicated load). The shear stress applied to the circumferential weld was determined as follows:

$$S = \frac{P}{c \times l} = \frac{1000}{(\pi)(0.83)(0.025)} = 16{,}700 \text{ pounds/(inch)}^2$$

where $S$ = shear stress in pounds/(inch)$^2$;

$P$ = applied load, in pounds;

$l$ = axial width of EB weld between tubes;

$c$ = circumference of weld between tubes.

The 1000 pound test load, applied to the specimens with three circle weld each, induced a 3,030 pounds/(inch)$^2$ shear stress over one total weld, as determined from the following:

$$S = \frac{1/3\ P}{\pi[D_o^2 - D_i^2]} = \frac{(1/3)(1000)}{(\pi)\ [(0.375)^2 - 0.325)^2]} = 3{,}030 \text{ pounds/(inch)}^2$$

where $D_o$ = outside diameter of circle weld between tubes, in inches;

$D_i$ = inside diameter of circle weld between tubes, in inches.

Based on those stress values, the shear load carrying capability of the EB doubler welds was considered satisfactory.

## Distortion Examination

Examination and dimensional inspection of the full-length T-111 honeycomb tube, containing five EB welded (90 kv - 5 ma) doublers, was conducted to determine the extent of distortion, and establish whether postweld sizing would be necessary for subsequent assembly operations (tube-to-tube and tube-to-header welding). The welding was conducted, using a randomly selected tube, and indented and backfilled ring inserts. The inserts had been sized, after backfilling, to provide an adequate fitup with the honeycomb tube for EB welding. The specially constructed, split, expandable molybdenum mandrel (Figure 17) was employed during this processing. The pattern of the EB welds was the same as that required in the honeycomb tubes of a full-scale assembly; i.e., two circumferential welds around each doubler edge, and three circle welds around the indentations of the center doubler only. The results of the dimensional measurements will be discussed in ensuing paragraphs.

The tube was inspected at the following processing stages:

1. As-received;
2. After installation of welding fixture;
3. After EB welding, prior to fixture removal;
4. After fixture removal.

The average outside diameter of the as-received tube was 0.855 inch, with a variation of ± 0.0012 inch. The average diameter became 0.8540 inch after the fixture installation, and the variation became ± 0.0014 inch. After welding and removal of the fixture, the average diameter was 0.8537 inch, and the variation was ± 0.0024 inch. The net diameter change was 0.0015 inch.

The tube straightness measurements at the four stages of fabrication yielded maximum deviations from perfect straightness of 0.007, 0.0087, 0.0101, and 0.0107 inch, respectively. The net overall straightness change was thus 0.0037 inch. Axial distortion of this extent could probably be accommodated in the subsequent GTA tube-to-tube welding

operations, based on the results obtained from concurrently conducted welding trials on a seven-tube bundle (6-inch-long tubes). Those results showed that satisfactory GTA welds could be achieved between tubes initially separated an amount in excess of 0.006 inch. Further comments related to the tube-to-tube GTA welding are made in later paragraphs.

In addition to the above overall dimensional measurements, the doubler areas were inspected in detail. The maximum distortion observed from these measurements was at the heat-affected zone (HAZ) of the EB welds. The maximum surface straightness variations across the five doubler stations are summarized in the following tabulation:

| Doubler Station* | Maximum Variation in Surface Straightness (Inches) |
|---|---|
| 1 | 0.0043 |
| 2 | 0.0053 |
| 3 | 0.0088 |
| 4 | 0.0033 |
| 5 | 0.0196 |

*Increasing station number indicates increasing distance from a stop at the end of the split, expandable, molybdenum mandrel. Positions correspond to desired doubler locations in the model assemblies.

The greater variations at Stations 3 and 5 better indicate the localized straightness variations across any given doubler, because the axial spacing between measurements at those positions was less than at the others. Thus, the maximum differential tubing distortion across the narrow EB weld areas was measured at two stations only. The distortion at Station 5 (0.0196-inch straightness variation) indicated that the employment of different EB parameters might be advantageous. The most appropriate substitute parameters would be 110 kv - 2.5 ma, and a welding speed of 58.5 inches/minute. No additional sample assembly was prepared to determine if those parameters were superior to the 90 kv - 5 ma combination.

Graphs depicting all of the above described dimensional inspection data were prepared and sent to the NASA Program Manager for review and dispensation.

The molybdenum fixture was broken in two places during its removal from the tube. Although it was still usable for additional EB welding experimentation, consideration should be given to the construction of an alternate fixture. Such a fixture could be constructed of stainless steel with molybdenum inserts in the immediate vicinity of the weld areas.

The tube-to-header joining problem was resolved though the use of extended length doublers which protrude past the end of the tube section. The fixture mandrel was modified to accommodate these longer doubler attachments to full-length honeycomb tubes.

## TUBE-TO-TUBE GTA WELDING

The automatic internal GTA welding process was studied for joining of 0.850-inch-OD by 0.010-inch T-111 honeycomb tubes to each other along mutual lines of axial contact. The results of the initial parameter study are presented in Table V. Two, 4-tube-bundle sample assemblies were employed in the study; effectively zero axial clearances were maintained between the tubes prior to welding. Short tube sections were used because the weld positioning fixture had not been completed at that time. Visual examination of these preliminary tube-to-tube welds indicated that a power input of 34 amperes and 24 volts produced complete penetration when coupled with an axial travel speed of 33 inches per minute. The welding arc was initiated at the extreme ends of the tube sections, to obtain maximum weld lengths. Since no internal end support fixture had been used, the effective welding heat flux was larger than desired at those locations, and resulted in a large amount of end distortion. The observations made for the initial parameter studies were therefore based only on the remaining portions of the welds. Thus, the above indicated welding parameters produced the minimum tubing distortion of those combinations which yielded complete penetration welds.

Visual, ultrasonic, fluorescent penetrant, and radiographic inspection were employed to define the quality of the welds produced in the initial parameter study. Comparison of the results from these tests established that defective or acceptable tube-to-tube GTA weld areas could be identified by visual examination of the root sides of the welds. To guarantee the acceptability of tube-to-tube welds in a hardware assembly, the ultrasonic

TABLE V

RESULTS OF INITIAL GTA WELD PARAMETER STUDY FOR JOINING OF T-111 TUBES ALONG AXIAL LINES OF CONTACT

| Joint Number[2] | Welding Variables[1] | | | Fusion Zone Dimensions[3] | |
|---|---|---|---|---|---|
| | Current (Amperes) | Voltage (Volts) | Axial Travel Speed (Inch/Minute) | Face (Inch) | Root (Inch) |
| 5-8 | 25 | 21.5 | 33 | 0.060 | -- |
| 6-7 | 25 | 21.5 | 33 | 0.070 | 0.035 |
| 5-6 | 28 | 22.0 | 33 | Not Determined | |
| 7-8 | 30 | 23.5 | 33 | Not Determined | |
| 1-2 | 33 | 23.0 | 33 | Not Determined | |
| 2-3 | 34 | 24.0 | 33 | 0.076 | 0.038 |
| 1-4 | 35 | 23.5 | 33 | 0.080 | 0.045 |
| 6-8 | 35 | 24.0 | 33 | Not Determined | |
| 3-4 | 35 | 24.0 | 33 | 0.080 | 0.026 |

(1)
a. All welds made in a helium environment, using a Miller, Inc. Welding Machine - Model ESR 400. Tubes GTA tack welded at their ends to maintain contact along axes.

b. An existing special constructed water-cooled torch was modified for this study, using a 1/16-inch bent tungsten electrode.

(2)
a. Eight individual tubes used to form two four-tube bundles.
b. Tubes were 0.850-inch-OD x 0.010-inch-wall x 8-inch-long T-111.
c. Joint number identifications were arbitrary.

(3)
Weld dimensions obtained from microstructural examination.

technique could be employed as a supporting quality assurance measure. The metallographic examination of the initial specimens demonstrated that the welds were metallurgically sound, regardless of the parameters used in preparation. Typical microstructures of two of the initially GTA welded tube-to-tube specimens are shown in Figure 40. That examination also confirmed that the visual inspection of the root sides of GTA welds could satisfactorily establish their integrity.

## STRENGTH REQUIREMENTS

The strength requirements for the axial tube-to-tube welds were that each be capable of withstanding an applied axial load of 33 pounds per inch of weld length. Three test specimens were welded using the following parameters: power input - 34 amps and 24 volts; travel speed - 33 inches per minute; zero clearance between tubes. The special adaptors, prepared for load transmission during mechanical testing, were also used to maintain the alignment and fitup of the test specimen tubes for welding. Excluding the circular weld spots at the start of the axial fusion zones in the mechanical test specimens, the characteristics of the remaining portions were equivalent to those observed in earlier specimens, prepared using the same parameters. This was true because the fixtures were well removed from the actual weld locations. However, greater localized deformation was present in the weld heat-affected zones of the mechanical test specimens. This behavior was attributed to a small difference in axial alignment of the tubes in relation to the adaptors during welding, which produced radial forces on the tubes greater than desired. After one hour postweld annealing at 2400°F, the three specimens were subjected to 1000-pound axial loads (crosshead travel speed during loading was maintained at 0.01 inch per minute) for qualification; no weld failures were observed. The shear stress induced in the welds of the test specimens was determined as follows:

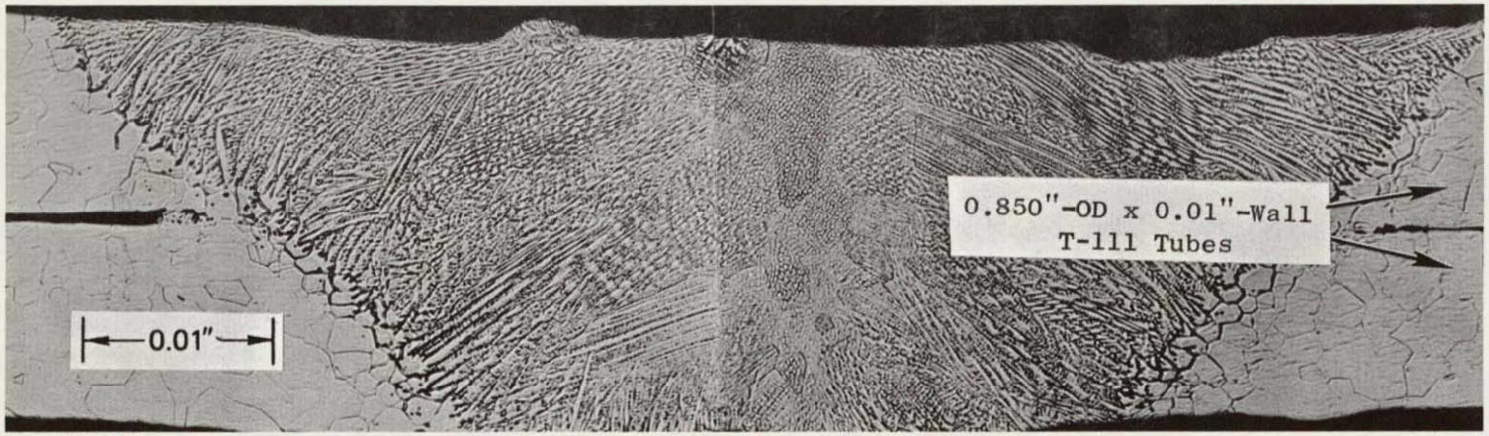
$A_o$ = shear area of the circular weld spots =

$$\left[\frac{\pi}{4} \times (\text{spot diameter between tubes})^2\right] \times 2$$

$$= \left[\frac{\pi}{4} \times (0.23 \text{ inch})^2\right] \times 2$$

$$= 0.083 \text{ inch}^2$$

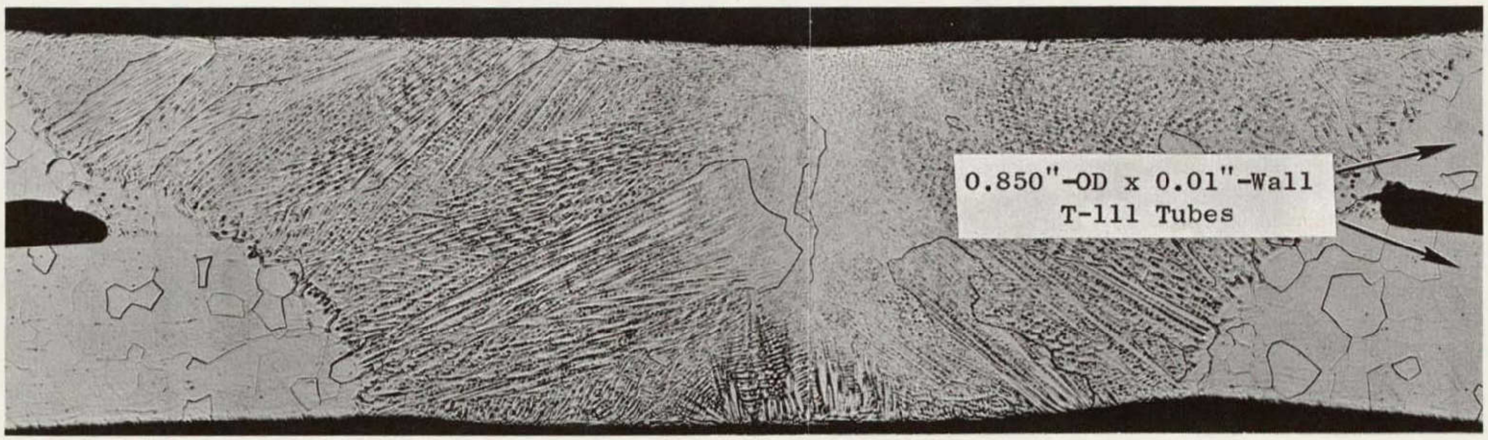
Weld No. 2-3 (34 amps - 33 Inches Per Minute)




G87011A 100X G87011B



Weld No. 1-4 (35 amps - 33 Inches/Minute)




G87031B 100X G87031A

Figure 40. Representative Microstructures of Initial GTA Tube-to-Tube T-111 Weld Parameter Specimens. Etchant: $NH_4F$, $HNO_3$, $H_2O$

$A_1$ = shear area of axial welds =

$$[(\text{length of welds}) \times (\text{width of welds between tubes})] \times 2$$

$$= [(0.77 \text{ inch}) \times (0.065 \text{ inch})] \times 2$$

$$= 0.100 \text{ inch}^2$$

$$\% \text{ of load carried by axial welds} = \frac{0.100}{0.100 + 0.082} \times 100 = 55\%$$

$$S = \frac{P_1}{A_1} = \frac{(0.55)(1000)}{0.1} = 5{,}500 \text{ pounds/(inch)}^2$$

Assuming a weld with a shear cross sectional area equal to 0.065 inch$^2$ (weld width - 0.065 inch, weld length - 1.0 inch), the stress induced by a specified qualifying load of 33 pounds would equal 500 pounds per inch$^2$. Comparing that figure, with the above shear strength value, demonstrated the excellent capability of tube-to-tube welds, prepared as described, to withstand the stresses expected in service.

EFFECT OF INTERTUBE SPACING

The effects of intertube spacing on the tube-to-tube GTA welding was studied by the preparation of a seven-tube bundle, using 6-inch-long tubes without doubler inserts. The purpose of the test was to determine the maximum clearance between tubes, which could be tolerated during welding. The tube bundle was held together and supported at one end using the end support flange shown in Figures 18 and 22. The special weld positioning fixture, developed for fabricating tube-to-tube welds, was used for the first time in this portion of the study. The clearance between tubes was varied by inserting appropriate shim stock between a given tube pair opposite to the supported ends.

The results of the welding trials are presented in Table VI; Figure 23 shows the orientation and identification of the joints. It was apparent from the initial weld No. 1A that the previously established welding parameters required modification to compensate for the effects of the end support fixture, which was used for the first time in these trials. The second weld No. 1B was therefore made at essentially double the weld heat input by decreasing weld speed to 15 inches per minute. This weld and weld No. 7A produced excellent weldments with no indication of burnthrough

TABLE VI

RESULTS OF TUBE-TO-TUBE GTA WELD TRIALS FOR DETERMINATION OF ALLOWABLE JOINT CLEARANCE

| Weld No. (Refer to Figure 23) | Welding Parameter* | | Joint Clearance (Inches) | Results |
|---|---|---|---|---|
| | amps | Speed - ipm | | |
| 1A | 34 | 33 | Zero to 0.006 (shim). | No weld along entire middle sections; sample clamped at both ends. Center clearance increased from 0.002 to 0.009 inches. |
| 1B | 34 | 15 | 0.006 shim at end, center clearance not determined. | Full penetration weld entire length. |
| 7A | 34 | 15 | Zero to 0.013 at center. | Full penetration weld entire length. |
| 7B | 34 | 24 | Zero to 0.008 at center. | Full penetration weld entire length. Narrower weld bead than 15 ipm joints. |
| 1C | 34 | 24 | $< 0.001$ at end, center clearance not determined. | Full penetration for $\sim 3$ inches from start, no penetration this point to end. |
| 1D | 34 | 24 | 0.001 at end, center clearance not determined. | Full penetration weld entire length. |
| Special weld two tubes in fixture | 34 | 20 | Zero - No wire bundling at free end. | Full penetration weld entire length. Tube ends parted during welding, then rejoined as weld approached. |

* All welds made in helium atmosphere, using Miller, Inc. Model ESR400 welding machine and Honeycomb Core weld fixture, drawing 47R199412.

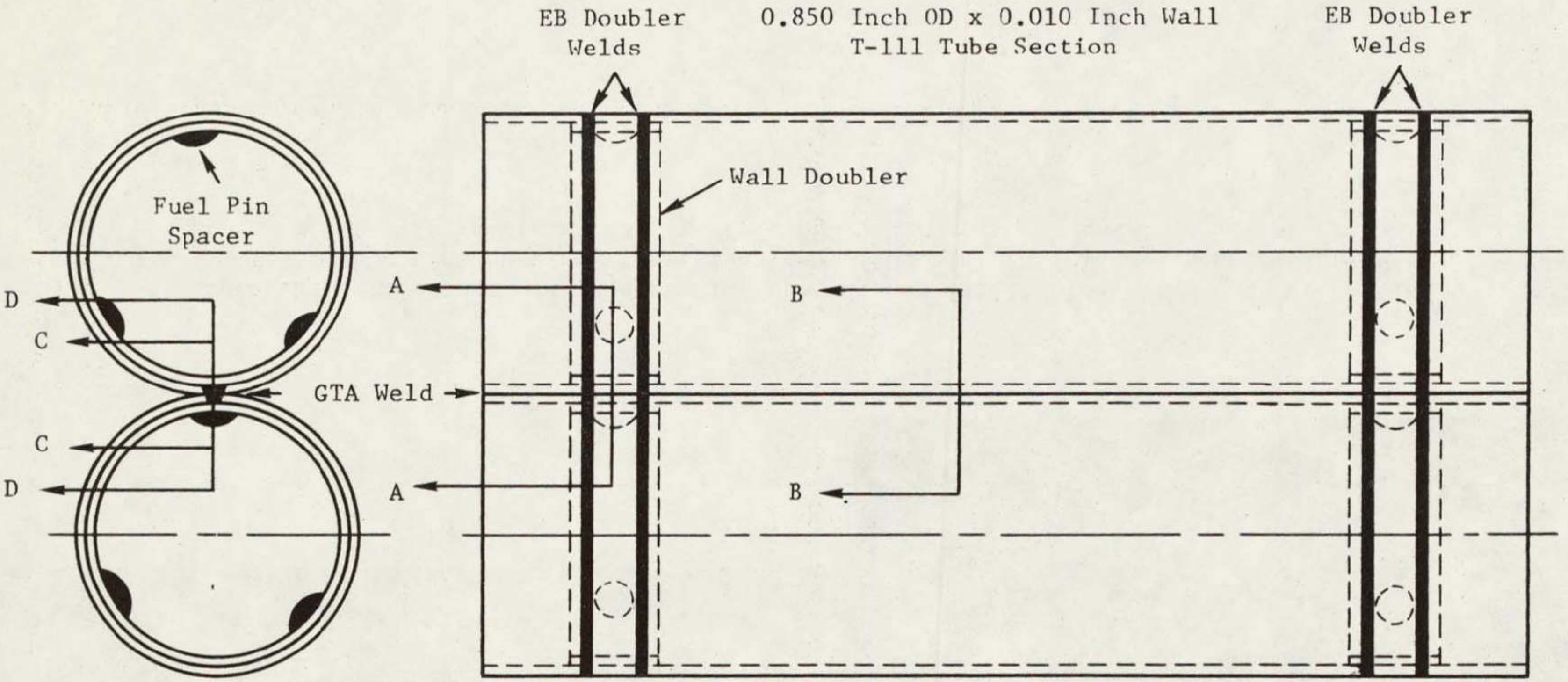
even at clearances between tubes of 0.013 inch initially. Weld No. 7B was an attempt to produce a more optimum weld width by increasing the speed to 24 inches per minute. Again, an excellent weld resulted. Welds 1C and 1D were made to evaluate welds between tubes already joined to a third common tube. For example, weld 1C joined tube 1 to tube 4, each being previously welded to tube 7. No burnthrough was found on either weld; however, weld 1C had complete fusion over only one-half its length. It was concluded that a 24 ipm weld speed produced a weld heat input slightly below the optimum. Therefore, a special weld joint was made at 20 ipm, 34 amps. These parameters produced the best overall joint characteristics. That final tube pair contained EB attached doublers at both ends; welding was initiated at the doubler location nearest the end support header. A further observation was that the distortion, at the end of the bundle next to the support header, was considerably less than experienced in previous trials. The distortion was also less there than at the other end of the test bundle.

The latter tube pair sample was sectioned for metallographic examination, as shown in Figure 41, to determine microstructurally, the effects of GTA welding over doublers, and to compare the weld at the mid-length of the tubes with previously fabricated welds. Figures 35 and 42 show the microstructures present at various positions along the tube-to-tube weld path. Complete weld penetration was evident at the center tube position, and through the doubler wall and tube at the end of the tubes, although the fusion zone dimensions varied considerably. The smaller weld at the end of the tubes may be attributed to either or both of the following reasons:

1. The heat conduction path at the ends was much greater than at the mid-point of the tubes;

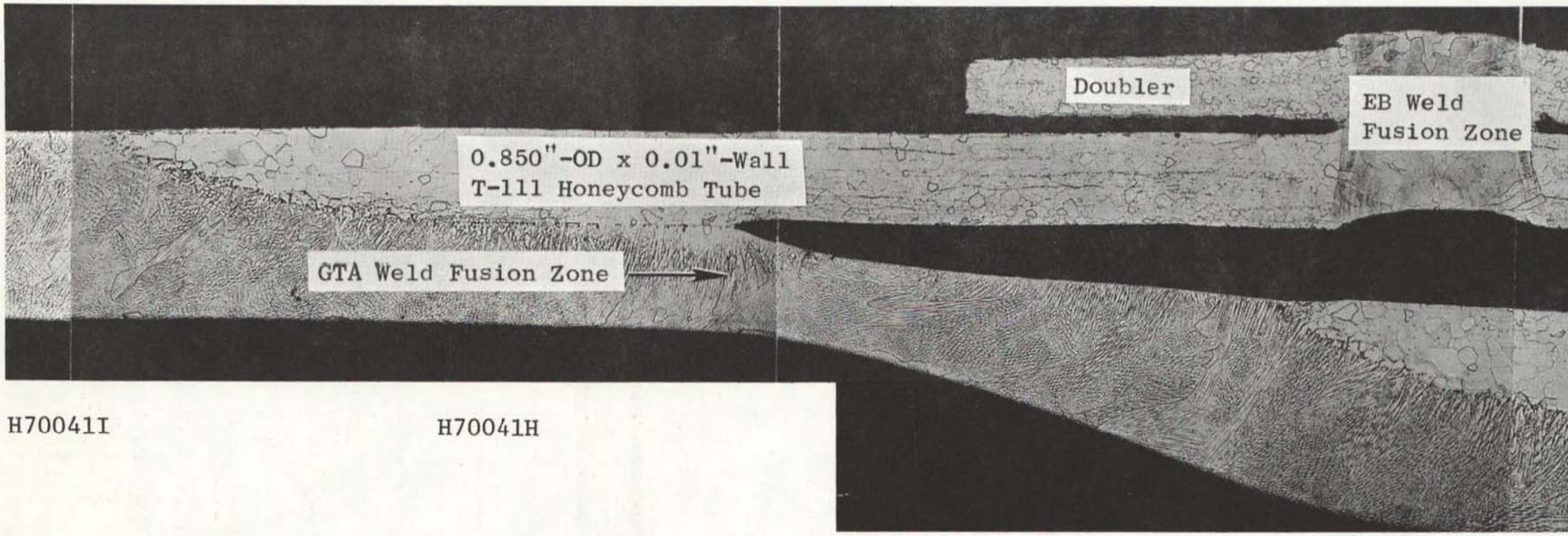
2. The time between arc initiation and the start of motion was too short to allow sufficient heat buildup at the doubler locations.

Since the doublers are to be attached by prior EB welding in construction of hardware, the described effect was considered of no consequence, regardless of the cause. The weld fusion zone dimensions at the tube mid-length were larger than those from previous trials; i.e., face = 0.096




Section A-A: Transverse Through GTA Weld and Wall Doubler Indentation/Fuel Pin Spacer.
Section B-B: Transverse Through GTA Weld Only.
Section C-C: Longitudinal Through GTA Weld/Transverse Through Doubler EB Welds.
Section D-D: Same as Section C-C, Except Through Opposite Doubler.

Figure 41. Metallographic Planes of Examination in Tube-to-Tube GTA Welded Specimen.




H70041I H70041H

H70041G 50X

Figure 42. Microstructure Through GTA Tube-to-Tube T-111 Welded Tube Pair at Doubler Location Showing Transverse View of Doubler EB Weld and Longitudinal View of GTA Weld. Etchant: $NH_4F$, $HNO_3$, $H_2O$

inch and root = 0.065 inch for 34 amps and 20 inchers per minute versus face = 0.076 inch and root = 0.038 inch for 34 amps and 33 inches per minute (see Figures 35 and 40). These measurements demonstrated that smaller welds were attendant with lower unit weld heat inputs, which also tend to reduce distortion effects. From that standpoint, the 33 inches per minute travel speed appeared superior for tube-to-tube GTA welding. However, it was necessary to employ the lower rate to achieve complete fusion of joints over their entire lengths, during the previous welding trials on tube-to-tube assemblies having intentionally tapered clearances. Thus, the 20 inches per minute travel speed, in combination with a welding current of 34 amps, appeared to be the most reliable, and those parameters were selected for subsequent preparation of full-length tube-to-tube sample joints containing no doublers. For the fabrication of a full-scale honeycomb core structure, varying the travel rate or heat input could be employed to achieve satisfactory tube bonds and also avoid excessive distortion. Further parametric studies would be necessary to establish optimum interrelated welding conditions. The microstructural examination of the above tube pair sample also demonstrated that the backfilled indentations of doublers located in the tubes adjacent to those containing the welding electrode were unaffected by the GTA tube-to-tube processing. The pattern of the tube-to-tube welds and the required indentation locations, at final assembly, would present situations equivalent to those encountered in the welding of the described sample. Thus, it is indicated that the fule pin spacers, or tubing ID protrusions, in the final hardware assembly would be unchanged, during the multiple tube-to-tube welding that would be conducted.

## MULTITUBE ASSEMBLY

The effects of GTA welding in multiple-tube assemblies was further studied by the preparation of another seven-tube bundle from 6-inch-long tubes each containing two EB weld attached doublers. The doublers were located 0.5 inch from either end of both tubes. The assembly, ready for GTA welding, is displayed in Figure 19. The individual tubes were inserted in the end support flange, and the opposite end of the tubes held together with Cb-1Zr wire. Note that no shims were placed between tubes in this test. The welding of the tube-to-tube joints was initiated over

the doublers next to the supported ends. The welding parameters of 34 amps and 20 inches per minute were used for all welds. The welds produced were examined and found satisfactory. The overall distortion, which occurred in this assembly, was noticeably less than that observed for the seven-tube bundle containing no inserts. However, the deformation at the unsupported ends was generally the same as that detected in the earlier trials. This was attributed to the fact that the welding had been allowed to progress completely to the end of the bundle. The effect could be minimized in future assemblies by stopping the cycle at the last doubler location.

The final experimentation performed, with regard to the T-111 tube-to-tube GTA welding, was the preparation of a seven-tube bundle from full-length (18 inches) honeycomb tubes, which contained no doublers. The GTA welding of the assembly was performed using 34 amps and a travel speed of 20 inches per minute. Individual welds were started immediately adjacent to the dummy header flange, and stopped approximately 0.25 inch from the other end of the tubes. The welding sequence was the same as that which would be used in the fabrication of a model or hardware assembly. The completed, seven-tube assembly is shown in Figure 43. No detailed inspections were performed on the bundle, but visual examination did provide the following observations.

## OBSERVATIONS AND CONCLUSIONS

1. The quality of the welds appeared generally satisfactory.
2. Longitudinal weld shrinkage had produced severe buckling at the mid-point of one of the outer tubes. Distortion, to a lesser degree, was also prevalent in the remaining outer tubes.
3. Considerable deformation was evident at the ends of the tubes.

Considering all of the data generated in the various GTA tube-to-tube welding trials in relation to the construction of a full-size core structure, the following comments are made:

1. The usage of either a welding power input or travel speed, which reduces the size of the weld fusion zone along the tube length, would be advantageous. Changing of those

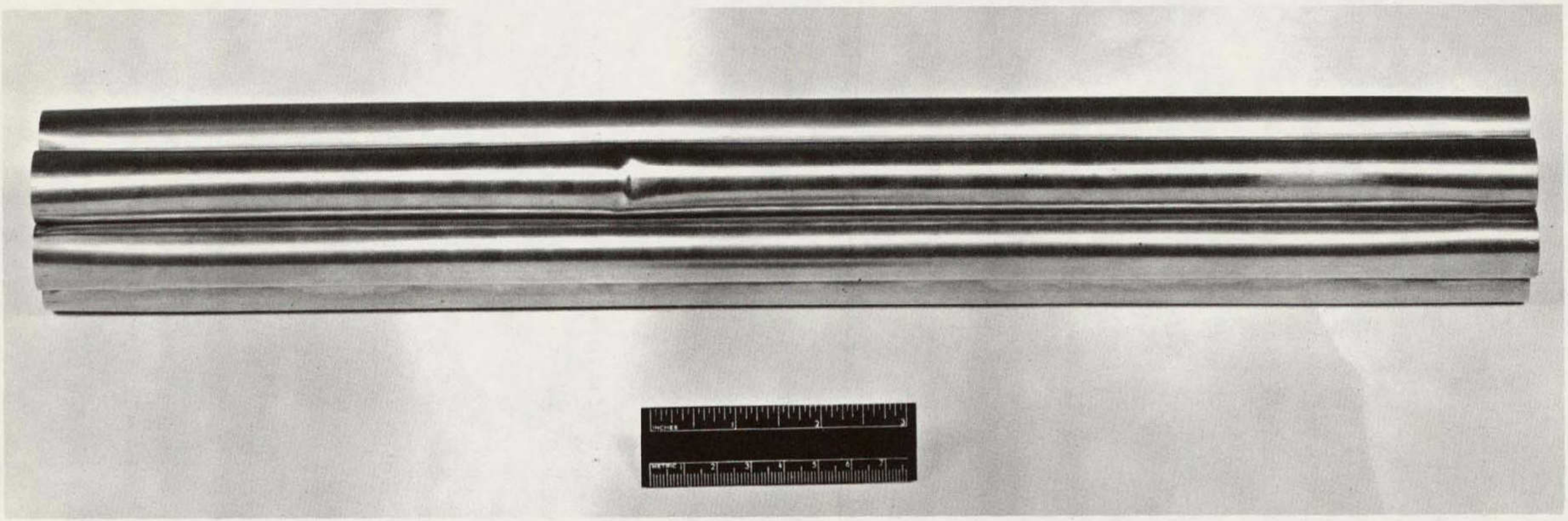


Figure 43. T-111 Seven-Tube GTA Welded Bundle - Full-Length Honeycomb Tubes. (Note Pronounced Buckling on Exposed Surface of One Tube.) (70-9-9)

parameters, while welding of any given joint is in progress, could be employed to compensate for variations in mass or heat rejection characteristics, thereby yielding more uniform welds, potentially exhibiting less overall distortion. The choice of parameters, other than those indicated, would necessitate additional parametric studies.

2. Welding should be initiated as far as possible away from the ends of the tubes, preferably over doubler locations.

3. All welds should be stopped as far from the tube ends as feasible. Alternately the end effects could be circumvented by using longer tubes, and removing the excess lengths after welding.

4. Intermediate in-process weld annealing cycles may be advantageous to minimize distortion.

5. The employment of minimal force to maintain the necessary contact of the tube would appear beneficial.

6. Conducting the individual weld operations on a start-stop-start basis, logically at the five doubler locations, would be desirable.

7. Improvements in the fixturing might be appropriate, especially along the length of the tube bundle.

## TUBE-TO-HEADER WELDING

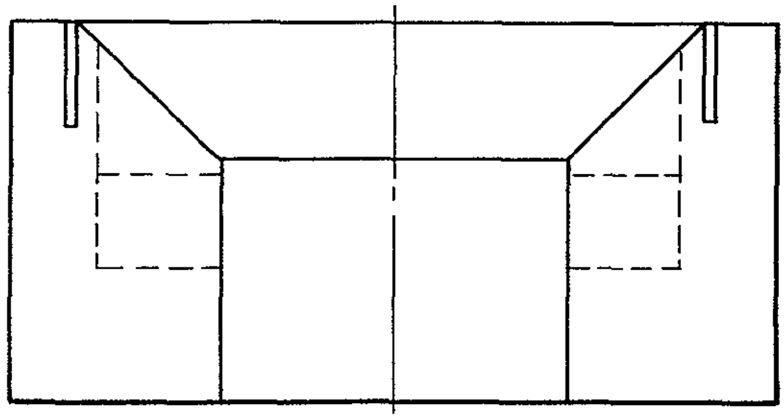
The fabrication of satisfactory T-111 tube-to-header welds was more difficult than initially contemplated. The basic problem of joining thick-to-thin sections by welding, required considerable experimentation to establish the combination of welding conditions and joint configuration which would reliably yield sound weldments. This problem was accentuated by the relatively high melting point and thermal conductivity of the T-111 alloy.

All of the tube-to-header welding was performed by the automatic, internal GTA process. The trials were performed using simulated T-111 header components, and short sections of the 0.850-inch-OD by 0 010-inch T-111 tubing. The initial configuration of the simulated header pieces was representative of a section through the originally conceived model assembly header flange, shown in Figure 2. Thus, it contained a 0.125-inch-deep circular slot for tube insertion, a conical-shaped section with holes to simulate eventual lithium flow passages, and recessed rectangular keyway slots. This configuration proved totally unacceptable for welding. Various geometric modifications were made in subsequent parts, and finally resulted in a satisfactory design All of the variations were considered with the final honeycomb core support structure in mind, such that the eventual product could be constructed using a header component having the developed detail design. Figure 44 presents schematically the transition configurations of the simulated header components used in the study. After the joining problem was resolved, tensile tests were conducted on several prepared assemblies to verify the weld load carrying capability. Following paragraphs will discuss the details of the tube-to-header joining development. The results of the tube-to-header welding trials are summarized in Table VII, excluding those pertaining to the final design configuration, which are presented in Table VIII. Figure 45 shows a schematic view of the initial simulated header components design configuration, and includes the general dimensional measurement locations, indicated in Table VII for a reference. Figure 46 displays the final general header configuration, and should be examined when considering the data presented in Table VIII. Figure 47 shows a representative tube-to-header parameter sample after GTA welding.

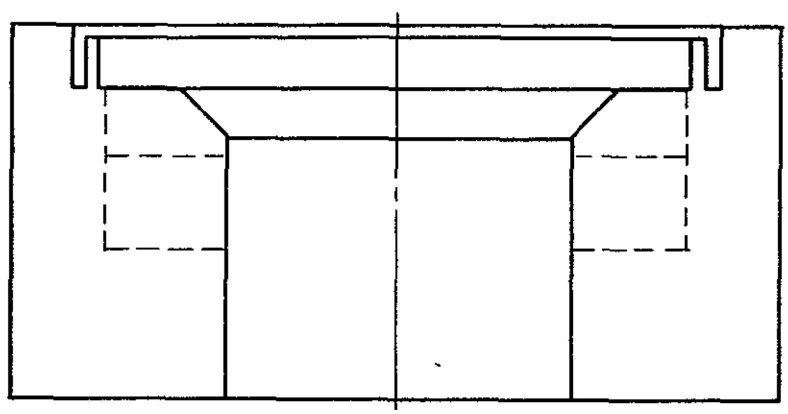
## INITIAL JOINT CONCEPT

Six header pieces were initially machined to the configuration previously mentioned Welding of the first of these specimens, P-1 and P-2, provided the first indication that geometric changes would be necessary to achieve satisfactory fusion The unsatisfactory nature of these welds was attributed to the drastic changes in total material

Configuration A



Configuration B



Configuration C

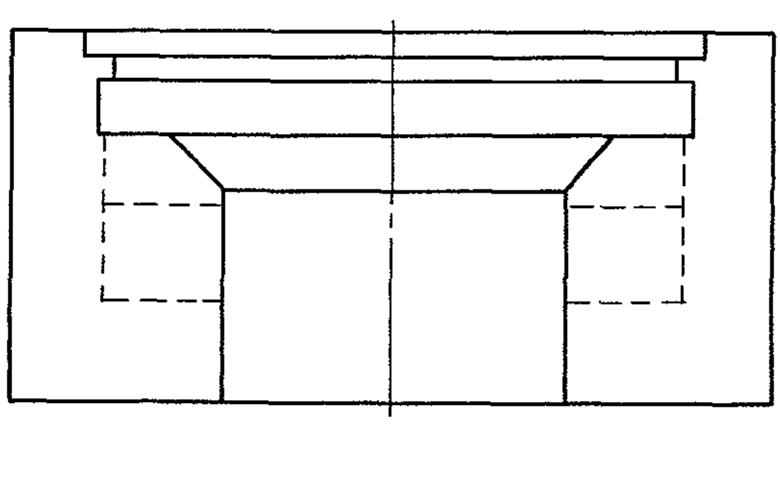


Figure 44. Sketch Showing Transition of Design Configuration for Simulated Header Components.

TABLE VII

SUMMARY OF RESULTS OF T-111 TUBE-TO-T-111 SIMULATED HEADER GTA WELDING TRIALS
INCLUDING INTERIM HEADER GEOMETRY VARIATIONS

| | Pertinent Header Dimensions (Inches) Refer to Figure 45 | | | | | Welding Variables/Conditions | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Welding Parameters | | | |
| Sample Number | A | Dia B | Dia C | Dia D | E | Electrode Position | Doubler Position | Amps | Volts | Travel Speed (rpm) | Remarks |
| P-1 | 0 125 | 0 850 | 0 828 | -- | -- | Intersection of tube and header | None | 50 | 16.5 | 2 5 | Hole blown thru tube at keyway |
| P-2 | 0 125 | 0 850 | 0 828 | -- | -- | 0 02" away from tube/header intersection, below surface "F" | None | 80 | 20 | 2 5 | Hole blown thru tube at keyway |
| P-3 | 0 125 | 0 850 | 0 828 | 0 810 | 0 03 | Intersection of tube and header | None | 60 | 17 | 2 5 | Hole blown thru tube at keyway |
| P-4 | | | | | | | | | | | |
| a) First Pass | 0 125 | 0 850 | 0 828 | 0 810 | 0 08 | Intersection of tube and header | None | 40 | 16 | 2 5 | Insufficient heat to cause fusion |
| b) Second Pass | | | | | | | | 60 | 17 | 2 5 | No fusion evidenced |
| c) Third Pass | | | | | | | | 75 | 18 | 2 5 | Satisfactory weld but tube buldged above fusion zone |
| P-5 | 0 125 | 0 850 | 0 828 | 0 810 | 0 08 | Intersection of tube and header | None | 75 | 18 | 2 5 | Too much tube melting |
| P-6 | 0 125 | 0 850 | 0 828 | 0 810 | 0 08 | 0 03" away from tube/header intersection, below surface "T" | None | 75 | 18 | 2 5 | Good weld characteristics, minimal distortion |
| 1 This and all subsequent samples machined with square end on rib | 0 08 | 0 850 | 0 828 | 0 810 | 0 08 | 0 01" below top of inner slot rib, or 0 025" below surface "T" | None | 45 | 16 | 2.5 | Holes blown thru tube at keyway Top of inner rib removed to permit welding below top surface of header to minimize tube bulging above weld |
| 2 | 0 08 | 0 850 | 0 828 | 0 810 | 0 08 | 0 02" below top of inner slot rib, or 0 035" below surface "T" | None | 45 | 16 | 2 5 | Electrode stuck in weld zone, remaining weld unsatisfactory. |
| 3 | 0 08 | 0 850 | 0 828 | 0 810 | 0 08 | 0.03" below top of inner slot rib, or 0 045" below surface "T" | Base of insert ring at top of inner slot rib | 45→104 | 16→21 | 2 5 | Weld power increased to cause fusion, arcing to face of counterbore occurred at high-energy input Sporadic welding evidenced |

TABLE VII (CONTINUED)

SUMMARY OF RESULTS OF T-111 TUBE-TO-T-111 SIMULATED HEADER GTA WELDING TRIALS
INCLUDING INTERIM HEADER GEOMETRY VARIATIONS

| Sample Number | Pertinent Header Dimensions (Inches) Refer to Figure 45 | | | | | Welding Variables/Conditions | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Welding Parameters | | | |
| | A | Dia.B | Dia C | Dia D | E | Electrode Position | Doubler Position | Amps | Volts | Travel Speed (rpm) | |
| 4 | 0 08 | 0 850 | 0 828 | 0.810 | 0 08 | Same as Sample No 3 | Base of insert ring at top of inner slot rib | 60 | 17 | 2 5 | Unsatisfactory welding of rib to tube observed, poor results from Samples No 1 thru 4 attributed to greater heat conduction, as associated with shallower slots |
| 5 | 0.140 | 0 870 | 0 828* | 0 776 | 0.140 | 0.015" below surface "F"(top of inner slot rib at surface "F") | Base of insert ring at top of inner slot rib | 50→45 | 16 | 2 5 | Rib melted without fusing to tube *EDM slot axially tapered |
| 6 | 0.140 | 0 870 | 0 828* | 0.776 | 0 140 | 0 035" below surface "F" (top of inner slot rib at surface "F") | Base of insert ring at top of inner slot rib | 45 | 16 | 2.5 | Rib melted without fusing to tube. *EDM slot axially tapered |
| 7 | 0 140 | 0 870 | 0 805* | 0.776 | 0 140 | 0 035" below surface "F" (top of inner slot rib at surface "F") | Base of insert ring at top of inner slot rib | 45 | 16 | 2.5 | Tube and Doubler Ring inserted to bottom of Header Slot *EDM slot axially tapered Thin rib intermittently melted away. Poor weld |
| 8 | Header piece machined to produce a single rib, 0.140" high by approximately 0 02" thick, above the main body (no slot) OD of rib machined to produce 0 005" diametric clearance between ID of tube and OD of rib prior to welding | | | | | 0 035" below top of rib | Base of insert ring at top of rib | 45 | 16 5 | 2 5 | Satisfactory weld obtained except for last 1/8" of joint No fusion noted over that part of joint because of separation of tube from the rib |
| 9 | Header piece machined as with Sample No. 8, except that diametric clearance (tube ID - rib OD) was 0 010" | | | | | 0.045" below top of rib | Base of insert ring at top of rib | 45→60 | Not Determined | 2.5 | Completely unsatisfactory weld characteristics |
| 10 | Header piece machined identically with Sample No 8 | | | | | 0.035" below top of rib | Base of insert ring at top of rib | 45→50 | 16 5 | 2 5 | Same results as obtained from Sample No 8, even though opposite sides of joint were tacked welded to potentially eliminate the tube/rib separation at end weld pass |

TABLE VIII

RESULTS OF T-111 TUBE-TO-T-111-SIMULATED-HEADER GTA WELDING TRIALS UTILIZING SELECTED HEADER DESIGN

| Sample Number | Weld Pass | Electrode Position: Radial | Electrode Position: Axial | Welding Parameters: Current (amps) | Welding Parameters: Travel Speed (rpm) | Remarks |
|---|---|---|---|---|---|---|
| 11 | 1 | 0.04" to 0.05" from tip to rib | 0.050" from surface of header | 25 | 2.5 | Very slight melting of filler ring. |
| | 2 | | | 40 | 2.5 | Same as first pass. |
| | 3 | | | 60 | 2.5 | Erratic fusion of joint tube distorted and cracked |
| 12 | 1 | 0.04" to 0.05" from tip to rib | 0.065" from surface of header | 80 | 2.5 | Complete fusion of joint. Approximately 1/8-inch-diameter void near end of weld. |

TABLE VIII (CONTINUED)

RESULTS OF T-111 TUBE-TO-SIMULATED-HEADER GTA WELDING TRIALS

| Sample Number | Weld Pass | Electrode Position: Radial | Electrode Position: Axial | Welding Parameters: Current (amps) | Welding Parameters: Travel Speed (rpm) | Remarks |
|---|---|---|---|---|---|---|
| 13 | 1 | 0.04" to 0.05" from tip to rib | 0.005" from surface of header | 80 | 2.5 | Very poor weld; axial electrode position shift noted. Electrode set at 0.065" below header face originally. Electrode tip was sharp. Electrode reset at 0.065" for 2nd pass. One-second time delay between arc initiation and start of electrode rotation. |
| | 2 | | 0.065" from surface of header | 90 | 2.0 | No appreciable improvement noted in weld. No further electrode shift observed. Some time delay used as in first pass. |
| 14 | 1 | 0.04" to 0.05" from tip to rib | 0.065" from surface of header on the filler ring | 80 | 2.5 | Good weld, except that hole developed at 180° rotation from start of weld. 0.005" diametric gap between insert OD and header ID set prior to welding. Arc initiated at 0.005" gap location. One-second time delay used, as with Sample #22. No electrode shift noted; electrode tip was sharp. |
| | 2 | | 0.065" from surface of header | 90 | 2.0 | Hole remained, somewhat wider weld obtained. |
| | 3 | | 0.065" from surface of header | 110 | 2.0 | Heat input too high, weld width too large. Electrode burnback evident, indicates successive welds with one electrode are limited. |

TABLE VIII (CONTINUED)

RESULTS OF T-111 TUBE-TO-SIMULATED HEADER GTA WELDING TRIALS

| Sample Number | Weld Pass | Electrode Position | | Welding Parameters | | Remarks |
|---|---|---|---|---|---|---|
| | | Radial | Axial | Current (amps) | Travel Speed (rpm) | |
| 15 | 1 | 0.04" to 0 05" from tip to rib | 0.065" from surface of header | 90 | 2 | Generally good weld, except that holes were detected at 180° rotation from start of weld  Plane of weld not parallel to the face of the header, weld intersected with doubler EB weld at point of greatest deviation  Electrode tip was sharp. Axial electrode position shift noted  Electrode originally set at 0.065" below header face, estimate position at end of weld at 0 050" below face  Arc initiated at 0.005" gathered gap between insert OD and header ID |
| | 2 | | 0 075" from surface of header | 100 | 2 | Some improvement noted in weld, although hole remained at original position. Electrode position too low, caused some arcing to header piece at sharp corner. Weld satisfactory for determination of weld strength-specimen tensile tested. Shift in electrode position again noted - final position was 0.065" from header face Overall weld width too large. |
| 16 | 1 | 0.04" to 0.05" from tip to rib | 0.07" from surface of header | 100 | 2 | Equipment malfunction caused arc initiation between electrode base and surrounding Cb-1Zr block. First 90° of weld were very poor because weld heat was too high initially. Electrode tip was sharp. |

TABLE VIII (CONTINUED)

| Sample Number | Weld Pass | Electrode Position | | Welding Parameters | | Remarks |
|---|---|---|---|---|---|---|
| | | Radial | Axial | Current (amps) | Travel Speed (rpm) | |
| | | | | | | Axial electrode shift again observed Electrode burnback from this test and others indicates that a tip configuration change is needed Reducing the weld width requires placement of the electrode tip closer to the rib. Electrode shifting apparently caused by stress relaxation during welding Specimen will be used as dummy piece in subsequent welding to compensate for electrode relaxation |
| 17 | 1 | 0.02" from tip to rib | 0.065" from surface of header | 95 | 2 | Excellent weld characteristics observed. Welding heat may need to be increased Electrode tip hemispherical, no burnback evidenced. Weld width approximately 0.08" Electrode shift circumvented by making initial pass with new electrode on dummy piece (Specimen #25). Sample tensile tested and sectioned for metallography. |
| 18 | 1 | 0.02" from tip to rib | 0.065" from surface of header | 100 | 2 | Excellent weld characteristics. Welding heat increased as a result of metallographic examination of Sample No. 17. Sample trials tested. |
| 19 | 1 | 0.02" from tip to rib | 0.065" from surface of header | 100 | 2 | Generally good weld obtained, although slight burnback of the tube (above the weld line) was detected at one location. Results from last three tests indicate that an increased doubler thickness would be desirable. |

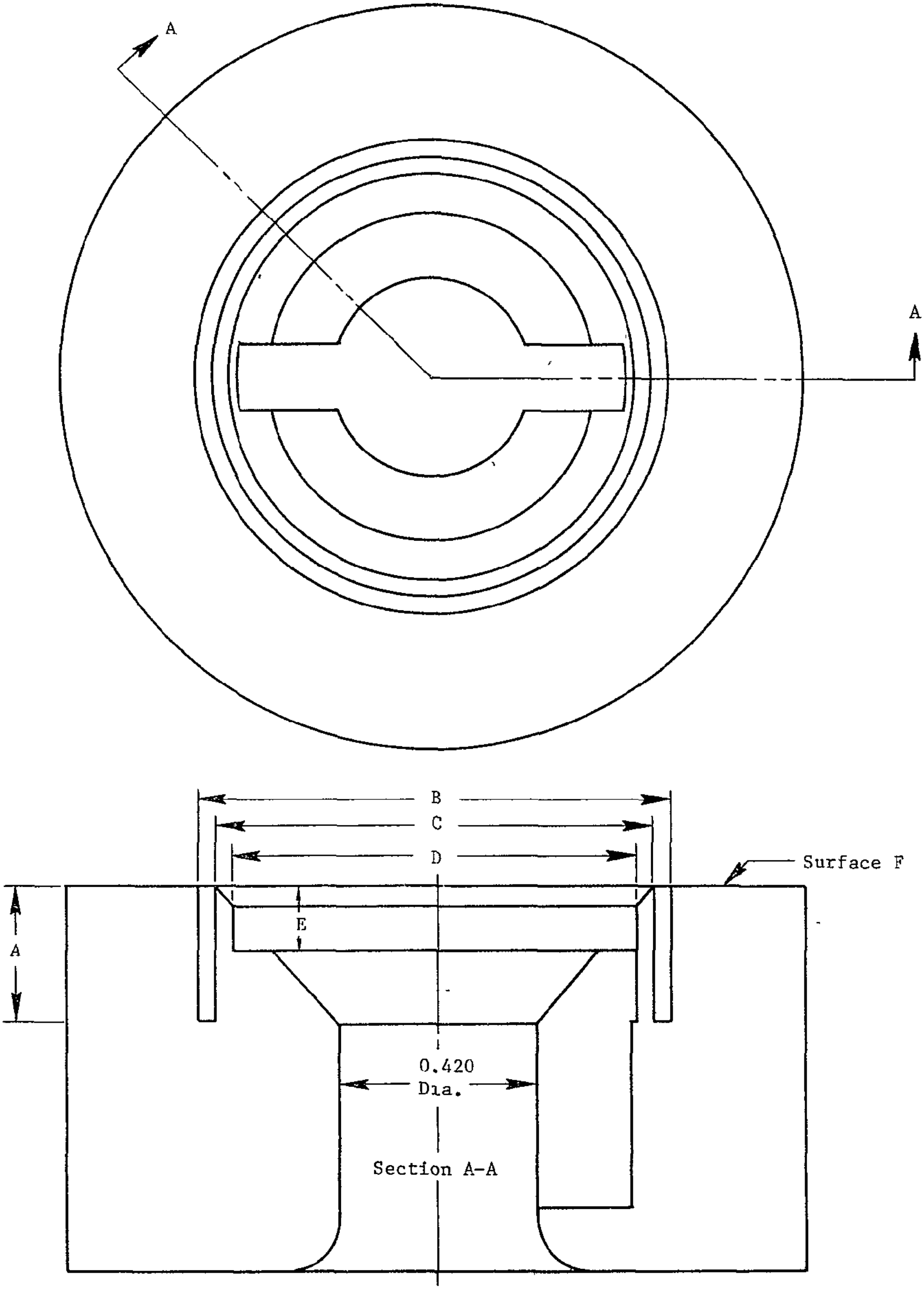



Figure 45. T-111 Simulated Header Specimen Configuration.

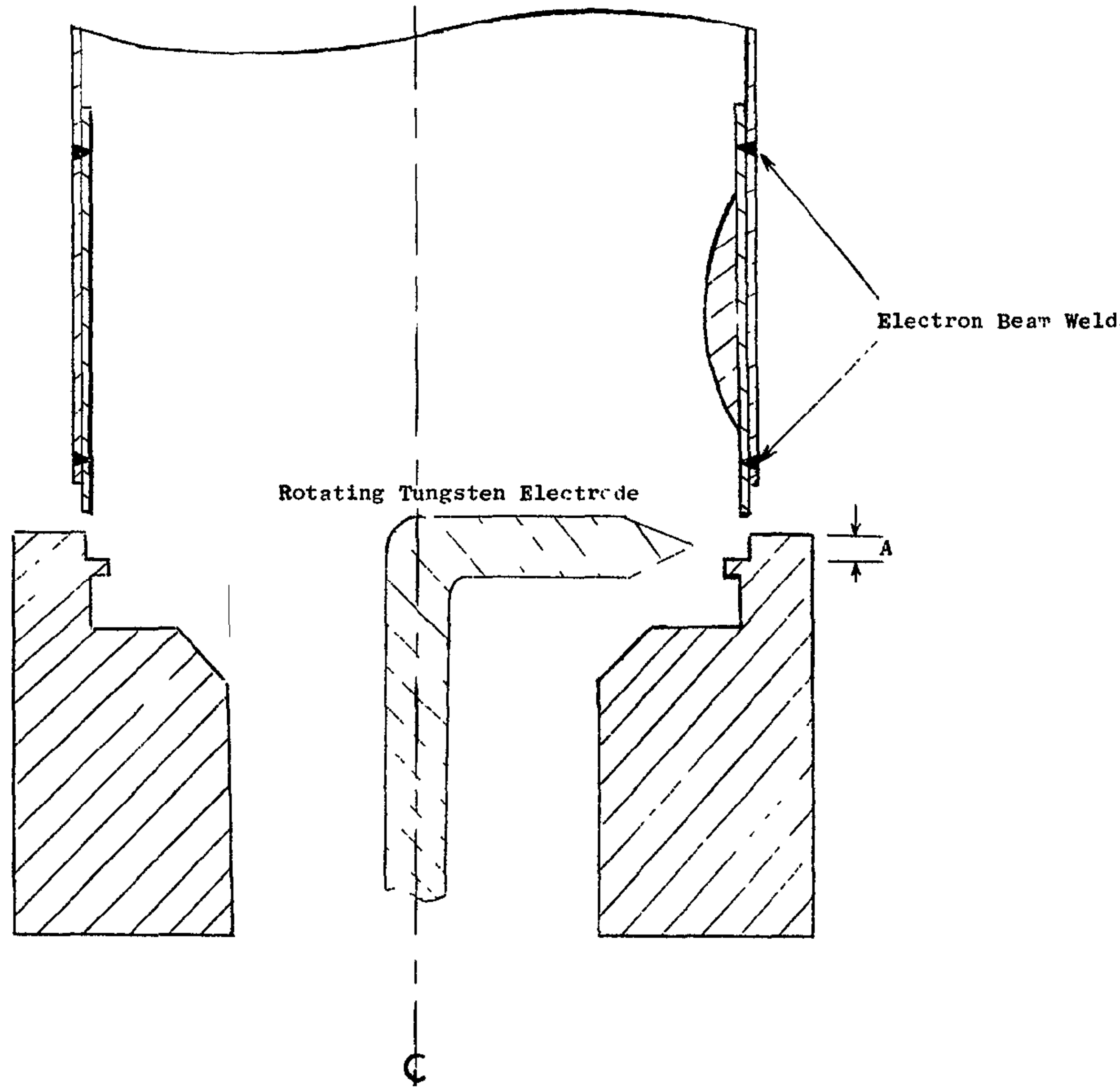



Figure 46. T-111 Simulated Tube-to-Header Joint Configuration.

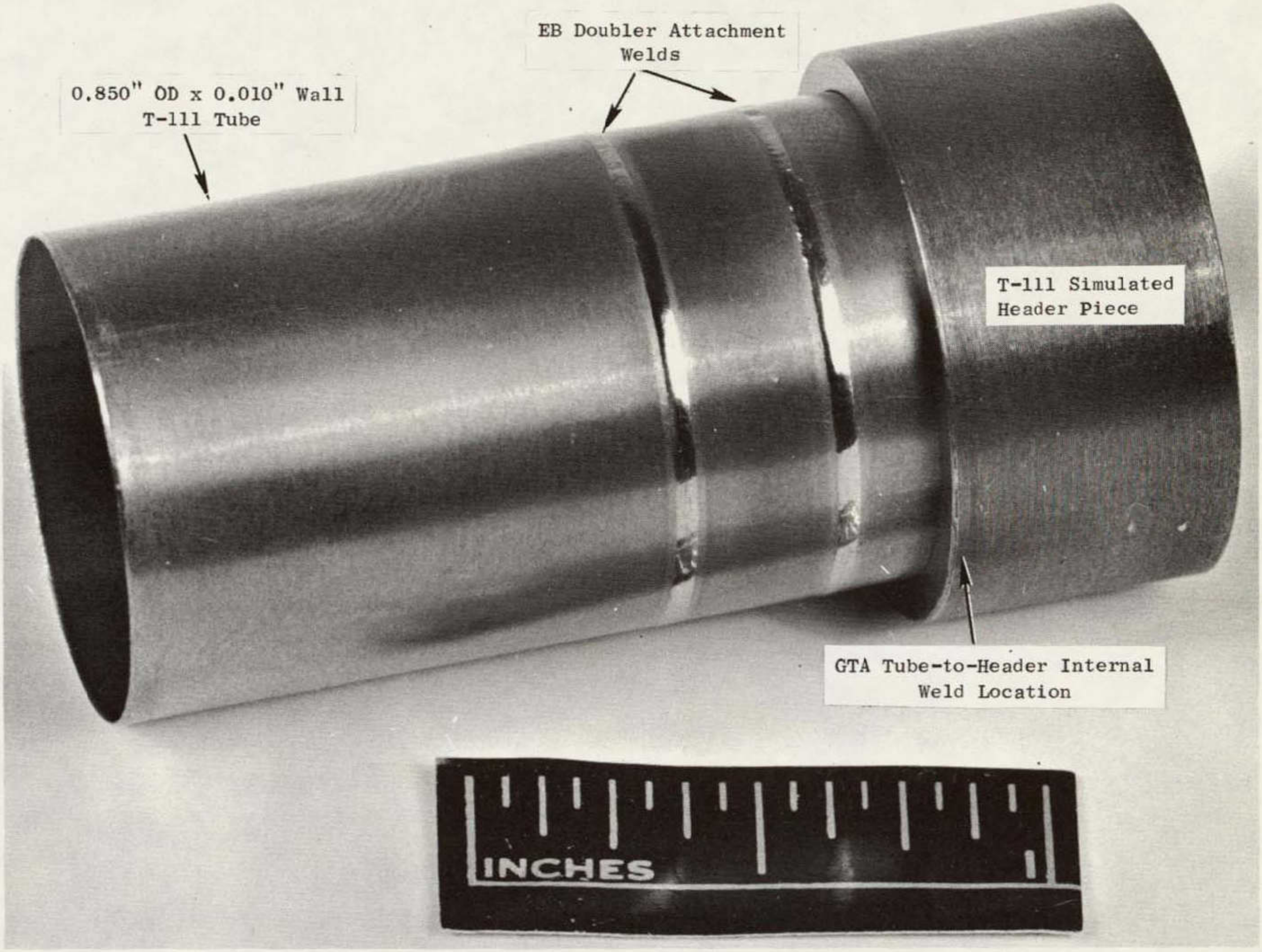



Figure 47. T-111 Tube-to-Simulated-Header GTA Weld Parameter Study Specimen. (70-1-9B)

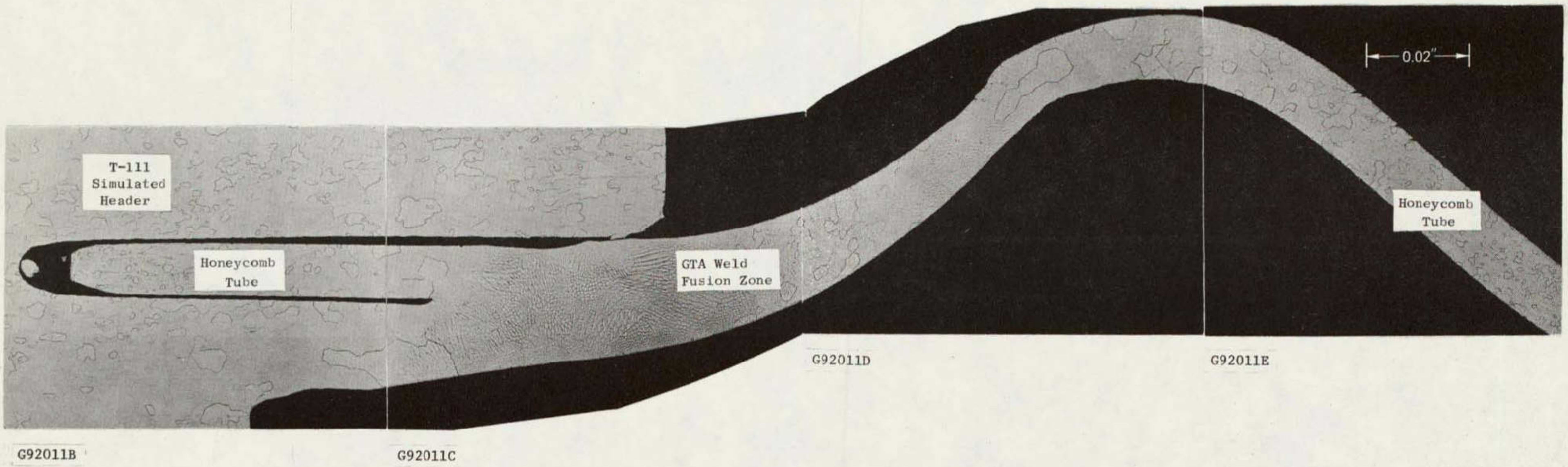



Figure 48. Microstructures of Tube-to-Header Weld Joint P-6; Note Extent of Tube Distortion Above Header Top Surface. Etchant: $NH_4F$, $HNO_3$, $H_2O$

thickness, (encountered on rotation of the welding torch) which could not be accommodated; i.e., when the torch passed from the conical-shaped section to the keyway slot, the power input was too great and caused excessive melting and burn-through of the thin-walled T-111 tubes. To potentially circumvent this difficulty, the remaining four simulated header components of the initial group were remachined to remove material from the conical shaped sections immediately adjacent to the inside diameter of the slots for tube insertion, as schematically shown in Figure 28 and 44. Thereafter, welds, P-3 through P-6, were made, using various parameter combinations to establish optimum conditions. The welding current and the axial position of the welding electrode were the main parameter variables in these trials. Visual examination of the latter specimens indicated that positioning of the welding electrode, 0.03 inch away from the tube and header intersection, over the header machined recess, produced the best weld characteristics, when coupled with a welding current of 75 amps.

Specimen P-6 was sectioned for microstructural examination to verify the quality of the GTA weld produced under the above indicated conditions. The examination was also used to determine whether some reduction in the slot depth could be made in subsequent samples and assemblies, to potentially reduce machining costs. The microstructure of the tube-to-header joint, P-6, is shown in Figure 48. The metallographic examination revealed that prohibitive tube distension had occurred above the weld, although an otherwise generally acceptable weld had been made. It was further indicated that a reduction in the depth of the slots for tube insertion could be made (from 0.125 inch to 0.08 inch), since no fusion was found 0.08-inch below the top surface of the header piece.

## MODIFIED JOINT CONCEPT

Based on the preceding observations, additional modifications in the geometry of the header pieces were considered to potentially eliminate the tube distension problem, and at the same time yield a configuration which could be more easily and inexpensively machined. The modifications were (1) reducing the slot depth to 0.08 inch, and (2) reducing the height of the vertical rib at the inside of the slots by 0.015 inch to allow the welds to be made below the top surface of the header. The



θ3

latter variation appeared appropriate for minimizing tube swelling above the welds because that area would be protected, in part, by the more massive header material. Four simulated header pieces were machined to this new configuration, ostensibly for preparation of mechanical test specimens. The new header design, relative to the original configuration, can be most readily compared by referring to Figure 44 - Views A and B. Subsequent GTA welding of the first two of these assemblies (Samples #1 and #2) proved to be completely unsatisfactory; i.e., holes were blown in the tubing in both samples, even though adjustments in parameters (power input) were made. The difficulty was attributed to an increase in the heat conduction or rejection path in the header pieces, associated with decreasing the depth of the header slots. When the power levels in welding were increased to compensate for that effect, the 0.010-inch tube wall immediately above the weld could not withstand the exposure to the welding plasma. To provide protection for the 0.850-inch OD tubing at that location, reduced diameter ring inserts were EB welded to the ID of the tube, as shown in Figure 49. These wall doublers were located such that the top of the header ribs were in contact with the base of the rings when the tubes were inserted. Again, the welding (Samples #3 and #4) was unsuccessful, implying that further geometric or welding technique variations were needed, primarily to provide either more protection for the basic tube above the weld than had been realized by the presence of the doubler inserts, or to diminish the heat rejection through the header, thereby allowing lower weld power levels to be employed. The processing variations investigated to potentially achieve the above described conditions were (1) increasing the depth of the slots for tube insertion, at least to that of the originally machined parameter study specimens; i.e., 0.125 inch, (2) increasing the thickness of the rib at the inside of the slots, and (3) positioning of the welding electrode further below the top surface of the header pieces.

Three more simulated header pieces were machined to configurations which incorporated the above design concepts, to continue the tube-to-header welding investigation. The slots in those parts were machined to a depth of 0.140 inch using electrical discharge machining (EDM) techniques. Two of the header pieces were counter bored inside the ID of the slots


Figure 49. T-111 Honeycomb Tube Section with EB Attached Doubler. (70-1-9C)

to produce ribs having thicknesses greater than those of preceding specimens (consistent with final hardware requirements, the maximum possible thickness was 0.026 inch at minimum counter bore diameter, 0.776 inch). The ID slot dimension of the third header piece was smaller than the other two, such that the inside rib thickness was approximately 0.010-inch. Inspection of the parts after machining indicated that the sides of the slots were tapered (base of slots narrower than at the top). This effect was attributed to electrode wear during EDM processing. Reduced diameter ring inserts were positioned and EB welded in two T-111 tube sections in the same manner that was indicated for earlier specimens. An insert ring was located and EB welded at the end of the tube for the third specimen, such that both the tube and ring were positioned inside the header slot before welding. The GTA welding of these three trial specimens (Samples #5, 6, and 7) was unsatisfactory. These results were attributed to the poor fitup of the tubes in the header slots.

Since the EDM process was unsatisfactory for machining of the narrow, 0.140-inch-deep slots, a new sample header geometry was devised, which would permit the usage of more conventional machining techniques to produce the desired interior rib dimensions. The new configuration eliminated that portion of the header which formed the outside of the slots. Thus, the interior rib was above the main body of the header pieces. Three additional specimens (Samples #8, 9, and 10) were prepared for further GTA welding; diametric spacings between the ribs' OD and the tubes' ID were set at 0.005, 0.010, and 0.005 inch, respectively. Again, prior to GTA welding, reduced diameter ring inserts were EB welded to the tubing, such that the end of the inserts butted against the top of the ribs. The tungsten welding electrode was positioned 0.035 inch below the top of the rib for Samples #8 and 10, and 0.045 inch below for Sample #9. The specimens, having the 0.005-inch diametric clearance, welded satisfactorily around most of the joints' circumferences, but tube expansion and separation from the ribs produced gaps which could not be bridged. The welding of the specimen with 0.010-inch diametric spacing was completely unsuccessful. These results indicated that a

further reduction in the tube-to-rib diametric clearance would be necessary to produce satisfactory welds. However, this concept would not be compatible with tube bundling requirements for a model assembly. Therefore, further trials using the "second generation" design concept (Figure 44-B) were abandoned, and a new approach conceived, which led to the final header configuration (Figure 44-C).

Prior joints were designed with the honeycomb tube on the OD of the header rib. This approach was selected because bundling of a honeycomb core in a hardware assembly required tube-to-tube line contact at the tube outside diameters. Tube dimensional tolerances also required approximately 0.005-inch diametral clearance between the tube ID and header rib OD prior to welding.

During the welding of samples #8,9, and 10, it became apparent that tube expansion during welding was the critical problem. This resulted in an increased joint gap which could not be accommodated as the joint neared completion. This effect had been partially masked in previous weld samples because the material on the outside of the slots in the header pieces tended to restrain tube expansion.

## FINAL TUBE-TO-HEADER CONCEPT

Based on the above analysis, the final tube-to-header joint design configuration, shown in Figure 46, was formulated. Three principal features of that design should be noted, (1) the weld is made between the header and an extended insert, (2) clearance (0.005-inch) to permit tube bundling is provided between the insert OD and header ID, (3) weld filler metal is provided by the machined ring feature on the header.

Initially, two tube-to-header samples were prepared to the Figure 46 configuration. The inserts extensions into the headers (dimension A, Figure 46) were nominally 0.035 and 0.060 inch, respectively. In each case, the insert OD was measured and the respective header machined to provide a 0.005-inch diametral clearance. Welding trials were conducted using the restraining fixture to prevent tube motion in the axial direction during welding. This simulated the expected condition in a tube bundle after tube-to-tube welds had been made. Refer to Table VIII for the results of these and all subsequent tube-to-header weld trials, conducted using the final header design geometry (Figures 44C and 46).

The initial trials were run with the 0.035-inch insert extension joint (Sample #11). Three weld passes were made before the weld current parameter was established that resulted in significant joint fusion. At that time, the tube was severely deformed and cracked by the multiple welding cycles.

The 0.060-inch insert extension joint (Sample #12) was then run. Complete fusion of the joint was achieved except for an approximate 1/8-inch-diameter void near the end of the weld. The joint was sectioned for metallographic examination and visual examination. The photomicrograph, Figure 50, illustrates the excellent joint quality achieved. Visual examination of the void area indicated a tight fit between the insert and header. The void was probably caused by erratic joint fusion at the start of the weld or by interaction between the weld puddle and filled dimple located adjacent to the void. Additional welding trials were necessary to verify the joint reproducibility.

The insert extension in the simulated header pieces was set at 0.06 inch for the next two specimens (Samples #13 and #14). The header pieces of those assemblies were machined to produce a 0.005-inch difference in diameters between the extended doubler OD and header ID. As with the Samples #11 and #12, a restraining fixture was employed to prevent axial tube motion during welding. The restraint fixture was also used, with appropriately spaced 0.005-inch-thick shim stock, for Sample #14, to produce a 0.005-inch diametric clearance between the insert OD and header piece ID at one location, which represents the worst anticipated condition for model assemblies tube-to-header welding.

The weld produced with Sample #13 was very poor; i.e., melting of the doubler occurred with only sporadic fusion to the header. This behavior was attributed to the mislocating of the tungsten electrode at a position above the filler rib. No significant improvement was observed after a second weld pass.

The results obtained for Sample #14 were markedly improved, although a small hole (~ 0.03-inch-diameter) was detected in the fusion zone approximately 180° from the starting position, after the first pass.

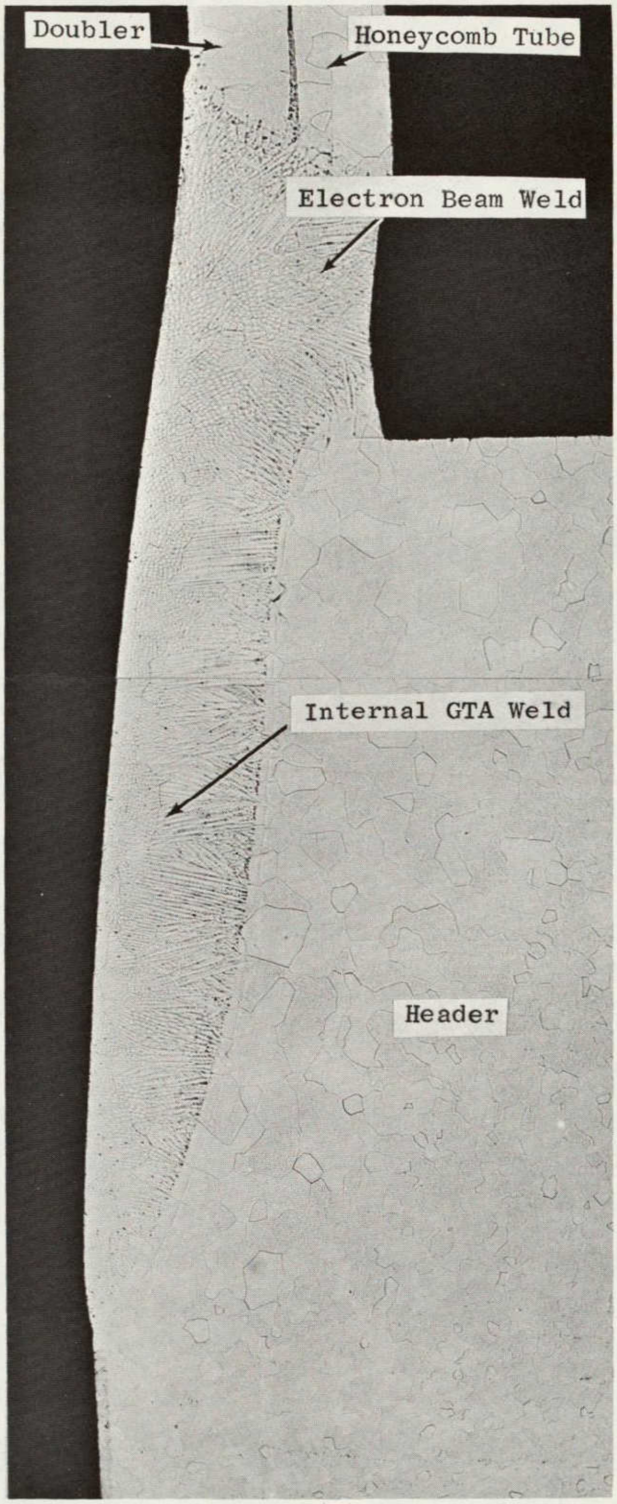



Figure 50. Typical Microstructure of Tube-to-Header GTA Weld Joint No. 12. (H61011 A & B) 50 X Mag. Etchant: $NH_4F$, $HNO_3$, $H_2O$

Since the fit-up of the insert and header forced their close contact in this area, and no filled dimple in the insert was close by, the hole formation was probably associated with a slightly insufficient welding heat. The defect noted in the weld of Sample #12 may also have occurred for the same reason. Additional weld passes on Sample #14 were not completely successful in repairing the defective area, although improvements in weld quality were noted.

Additional welding trials were necessary to establish whether increased power levels could eliminate the above described difficulty. These further studies of the tube-to-header joint were also required to provide information relevant to the electrode shape and position, and the interrelated effects of welding speed variations. Thus, three more samples were prepared for welding (Samples #15, #16 and #17). The insert extension into the headers was set at 0.06 inch for all three specimens. Two of the three header pieces were machined to produce a 0.005-inch difference in diameters between the OD of the doubler extension and the ID of the header; the diametric difference for the third specimen was 0.01 inch. Electron beam welding, to attach the extended inserts at the ends of the tube sections, was difficult because the previously prepared expandable molybdenum mandrel could not be employed. As a result, the EB welds, while generally satisfactory, contained some visible defects. Short doublers were EB welded at the opposite ends of the 3-inch tube sections for reinforcement. Holes were machined through the reinforced tube areas after tube-to-header welding to permit insertion of load transmission pins for postweld mechanical testing of these latter sample joints. A restraint fixture was used during GTA welding to prevent axial tube motion. Also, T-111 shim stock was inserted in each specimen before GTA welding to produce desired spacings between the doubler OD and header ID at specific locations.

The weld obtained with Sample #15 was generally good, but several small holes were observed in the fusion zone at approximately 180° rotation from the start of the weld. Some improvement was noted in the weld characteristics after the second pass, although complete fusion across the defective areas was not realized. An equipment malfunction caused the first 90° of the weld in Sample #16 to be very

poor. Multiple welding trials were performed, using that defective specimen, to investigate relative effects of welding heat input, electrode tip configuration and position, and rotational speed on the weld characteristics.

OBSERVATIONS AND CONCLUSIONS

Considering these latter trials, and all of the previous data generated in relation to the tube-to-simulated header specimens having the final header design configuration, the following observations and conclusions were made:

1. An axial shift ($\approx$ 0.015-inch) in electrode tip location occurred during the initial welding pass, because of stress relaxation in the formed tungsten electrode. The difficulty can be circumvented by making the initial pass with a new electrode on a dummy specimen.

2. The axial width of the welds varied with, not only the power input and rotational speed, but also with the distance from the electrode tip to the welds. Thus, with fixed power and speed, the burnback of the electrode (starting with a sharp tip) during welding resulted in welds varying from 1/8-inch to 1/4-inch wide. These widths were produced when the original tip-to-rib distance was set at 0.04 inch. Realizing a smaller weld and maintaining a constant weld contour required the use of a rounded electrode tip positioned closer to the rib in the header pieces; i.e., approximately 0.02-inch separation.

3. The types of weld defects encountered generally indicated that higher power inputs ($\sim$ 95 to 100 amps) were required to achieve sound welds.

Each of the above described factors, which influence weldment characteristics, was carefully considered before preparing Sample # 17. A hemispherical tipped electrode was selected to avoid burnback. The electrode tip was positioned axially at a point 0.005 inch below the top edge of the rib in the header piece (0.065 inch from the header bottom surface) and radially 0.02 inch from the rib ID. Residual forming stresses were eliminated from the formed electrode by making a prior

weld pass over a dummy header sample. A relatively high heat input was chosen for the welding operation. The tube-to-header weld, produced by adhering to the described conditions, was the first completely sound weld generated, and the assembly was helium leak tight. Sample # 17 was subsequently sectioned for microstructural examination transverse through the plane of the GTA weld. Figure 51 shows a typical microstructure of the sample weldment. That examination verified the excellent quality of the weld in that specimen and also pointed out that an increase in welding heat input could favorably be employed during the processing of future assemblies.

Two final tube-to-header weld specimens (#'s 18 and 19) were GTA welded to determine the reliability of the processing. All preparatory conditions were the same as those utilized for the welding of Sample # 17, except that the welding current was increased to 100 amps. The weld produced in Sample # 18 was excellent; however, in Sample # 19, a slight burnback of the tube (above the weld plane) was noted at one circumferential position. Avoiding this difficulty in the future could best be realized by using a heavier (up to 0.020 inch) walled, extended doubler.

Tensile testing was conducted on Samples 14, 15, 17, 18 and 19, after 2400°F for 1 hour heat treatments, to determine the load carrying capability of the tube-to-header welds. The results of these tests are summarized in Table IX. As the data point out, the tube-to-header weld in Sample # 15 could withstand stresses in excess of 25,000 pounds per $inch^2$. The failure of that sample occurred through a defective area in one of the prior EB doubler welds. The remaining four joints exhibited load carrying capabilities equal to, or greater than, the required qualification stresses for tube-to-header weld joints; i.e., $\sim$ 40,000 pounds per $inch^2$.

The T-111 simulated header components for the tube-to-header welding studies did not include the machined grooves, which would be required in final hardware assembly headers to permit locking of the nuclear fuel elements. It was initially intended that the simulated headers contain these fuel element retainer recesses to more closely approximate the final configuration. However, during the preparation of the header samples, it was demonstrated that the required internal recesses could

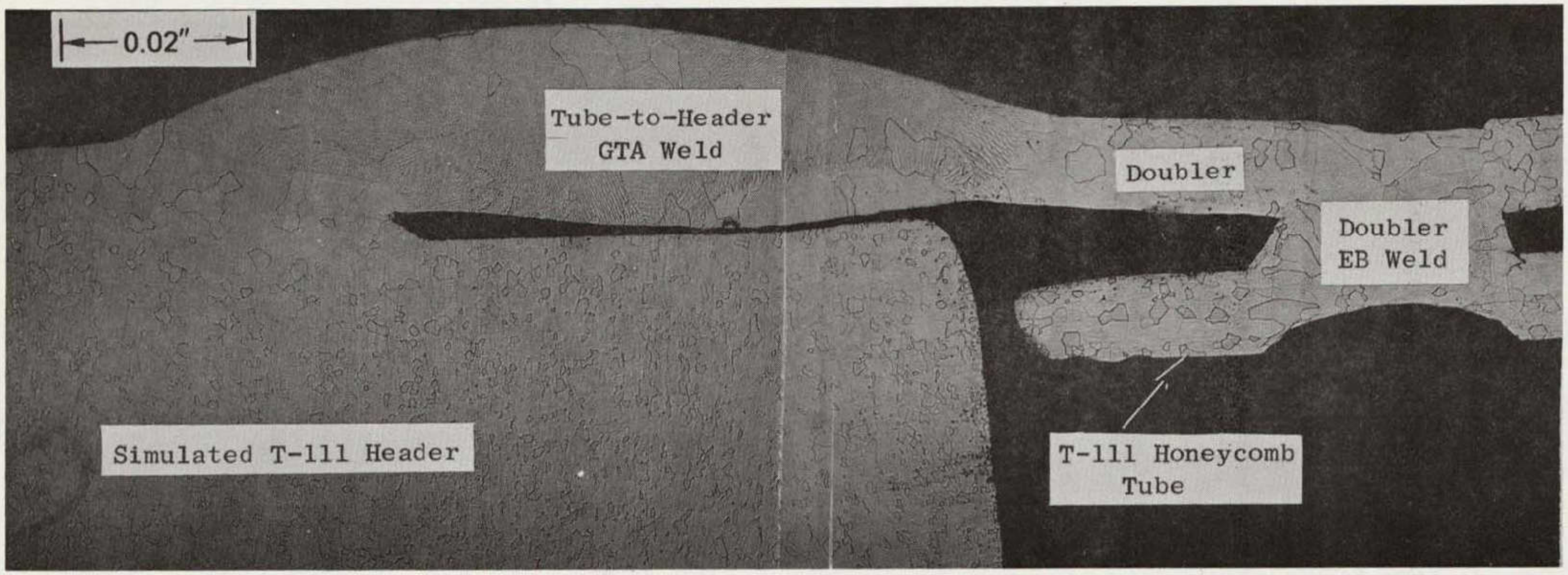



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Figure 51. Microstructure of Tube-to-Header GTA Weld Specimen No. 17.
Etchant: $NH_4F$, $HNO_3$, $H_2O$

TABLE IX

TENSILE TESTING OF TUBE-TO-HEADER GTA WELDS

| Specimen No. | Applied Load (Pounds) | Applied Stress* (ksi) | Remarks |
|---|---|---|---|
| 14 | 1320 | 50.8 | Failed through pinholes |
| 15 | 615 | 23.9 | Failed through lower EB doubler weld |
| 17 | 1000 | 38.8 | No failure - specimen sectioned for metallography |
| 18 | 1995 | 77.3 | Failed through pinholes |
| 19 | 2010 | 77.9 | Failed through pinholes |

* Stress based on 0.83 inch OD x 0.81 inch wall.

not be machined into a solid T-111 plate section, and an alternate technique was necessary for producing the retainer grooves in the header flanges The header geometry, schematically shown in Figure 52 was therefore devised to circumvent the machining problem and still meet the fuel element locking requirements. Pertinent features of that design configuration are as follows:

1. Conventional machining techniques can be employed to fabricate the component parts.
2. The side of the headers for tubes attachment would be identical with that required to produce satisfactory tube-to-header welds, as described above.
3. The cylindrical plug sections or fuel element retainers having the nozzle configuration at their centers would be electron beam welded to the basic headers.

A plan was formulated to determine the EB parameters for attaching the fuel element retainers to T-111 header flanges, although the experimental efforts were not implemented in the course of the study program.

## HONEYCOMB FABRICATION

Each of the manufacturing operations utilized to fabricate the T-111 honeycomb structure will have an obvious influence on those to follow. The extent of these influences must be established and taken into account during fabrication to meet the necessary assembly requirements. Thus, the processing procedures and sequence of welding must be carefully selected and followed to achieve that goal. In this study program, the techniques were developed for producing three distinct types of T-111 alloy weldments, which would be integral joints in the construction of a multiple tube-to-common header honeycomb fabrication. The investigation of each of those weld areas was conducted essentially separate from the other two, although efforts were made, where possible, to simulate the interrelated assembly conditions. Following paragraphs will discuss the honeycomb fabrication, from the standpoint of the integrated effects of the various joining processes, to indicate the

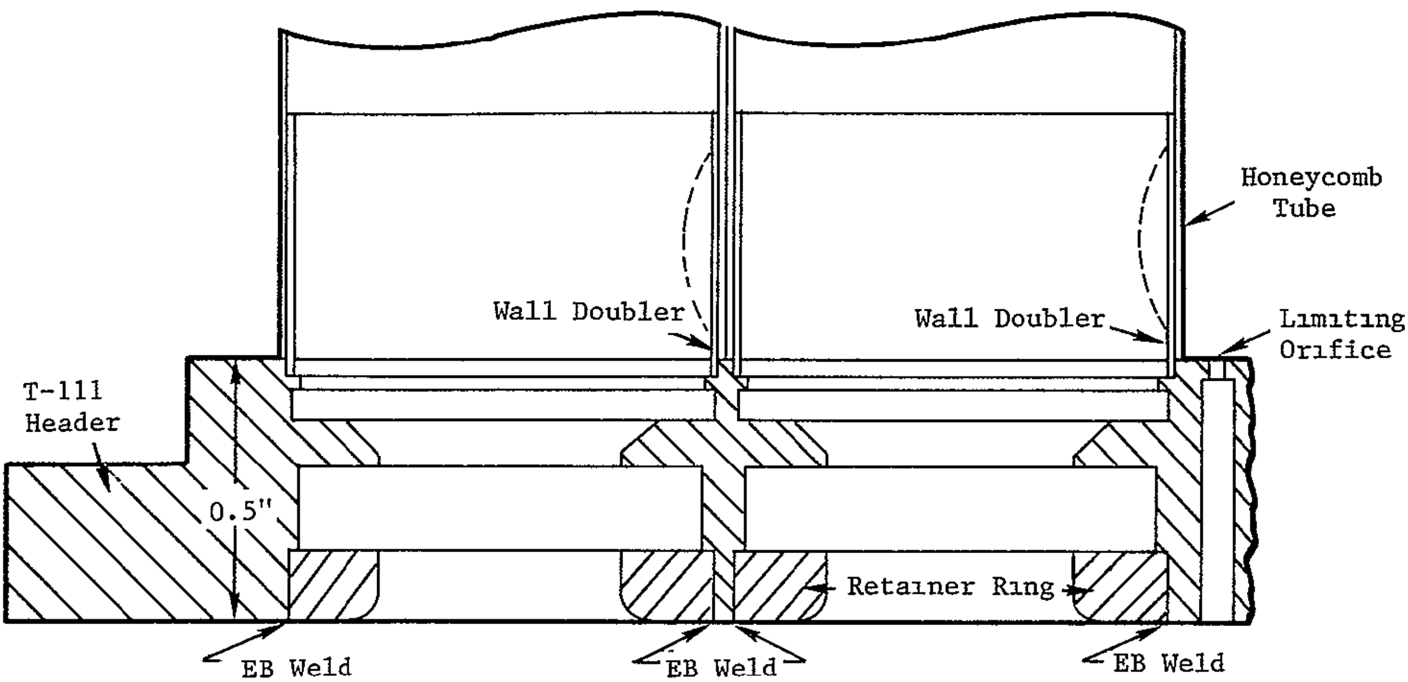


Figure 52. Final Developed Geometry of T-111 Header Components for a Honeycomb Assembly.

appropriate applications of the developed techniques, and to show some of the areas requiring further experimentation. Data from these additional trials would be necessary to define optimum overall procedures.

## FUEL PIN SPACERS IN HONEYCOMB TUBING

During the course of the investigation, most aspects of the fuel pin spacers production were considered and studied, relative to the honeycomb structure processing. As a result, the following procedures, sequence of operations, and pertinent processing details were generated and their implementation should result in the reliable production of these parts of the honeycomb assembly

1. Cut necessary T-111 rings for wall doublers from 0.827-inch OD by 0.010-inch wall tubing. Each honeycomb tube will require four 0.5-inch long insert rings and one 0.55-inch long insert ring.

2. Indent each T-111 ring at three equally spaced circumferential positions, using the tube indenting fixture (refer to Figure 14). The axial location of the indentations will be at the center of the 0.5-inch long rings, and offset approximately 0 06-inch from the center of the 0.55-inch rings. The depth of the dimples will be a constant for all rings - approximately 0.025-inch.

3 Cut sufficient 0.375 inch and 0.500 inch lengths of 0.062-inch diameter T-111 wire to provide the material required for backfilling the dimple cavities in the doubler inserts. These individual amounts of the reinforcement material are needed to completely fill the indentations which have different required depths in the model honeycomb tube inserts.

4. Clean formed insert rings and reinforcement material, per NASA Specification C-393666-2.

5. Place insert rings on the water-cooled molybdenum fixture (refer to Figure 15) in the GTA welding chamber and backfill outside dimple cavities with T-111 reinforcing material using heat from GTA welding plasma to cause flow and filling. Prior to these backfilling operations, the filler metal should be

formed into spheres by individually melting the cut lengths of T-111 rod in the machined recesses of the molybdenum fixture. Use a 0.062-inch diameter tungsten electrode centered over the indentations, helium shielding gas, and a welding current of 140 amps for the backfilling operations. Backfill individual dimple cavities over specific machined recesses in the molybdenum fixture to produce the required 0.033-inch and 0.043-inch indentation depths.

6. Visually inspect the reinforced rings to insure that desired filling characteristics have been produced.

7. Size all indented and backfilled inserts (doublers) to produce a uniform outside diameter (refer to Figure 13). Perform these operations in the tube indenting fixture, using the replacement lower ram/pedestal (refer to Figure 14).

8. Select 0 850-inch OD by 0 010-inch wall T-111 honeycomb tubes for use in models construction - 19 minimum required. Clean tubes and prepared doublers per NASA Specification C-393666-2. The amount of metal to be removed in cleaning should not exceed 0.0001-inch from the different surfaces.

9. Assemble five doublers for each honeycomb tube on the molybdenum expanding mandrel with the tapered drive pin in place (refer to Figure 16), and insert into the tubes Doublers positions are those necessary to place internal projections at required axial and radial locations in the honeycomb tubes (refer to Figure 3). The doublers at the tube ends, to be subsequently welded to the T-111 header flange, must extend out of the tubes a distance of 0 062-inch to facilitate fabrication of those welds. The EB welding fixture was constructed such that its usage will result in the required inserts protrusion past the ends of the honeycomb tubes.

10. Apply force to the drive pin to insure necessary contact of the doublers and honeycomb tube wall. Insert free end of drive pin in the chuck of the rotating drive carriage in the electron beam welding chamber. Carefully note subsequent weld positions

in relation to the end of the fixture and indexed scale placed alongside and parallel to the tube in the chamber.

11. Evacuate the chamber to a pressure $< 5 \times 10^{-5}$ torr, and electron beam weld all five doublers to the honeycomb tubes per NASA Specification C-393666-4, using the following parameters:

    a) Beam accelerating voltage - 90 kilovolts
    b) Beam current - 5 milliamps
    c) Beam focus - sharp
    d) Beam deflection/modulation - none
    e) Welding speed - 58.5 inches/minute.

    Two circumferential welds are necessary for each doubler attachment, center doubler also requires three equally spaced circular welds around each indentation (refer to Figure 13).

12 Visually inspect (borescope) root and face of all welds to certify their quality, radiographically examine any weld which has questionable penetration or appearance. Dimensionally check tubes for distortion - both localized and overall, spot check weld face dimensions - should measure from 0.020 to 0.030 inch wide. Reject any tubes having poor welds or prohibitive distortion.

13 Temporarily store prepared tubes in polyethylene bags in readiness for following operations.

FABRICATE TUBE-TO-TUBE AND TUBE-TO-HEADER WELDS

Following is a listing of some additional experimental tests that should be conducted to identify conditions most appropriate for fabrication of a multiple tube-to-common header T-111 honeycomb assembly (refer to previous sections of this report for certain other recommended tests pertinent to the individual joining areas):

1. Determine the optimum sequence for tube-to-tube and tube-to-header joints welding.

2 Determine parameters for EB attachment of 0.020-inch wall doublers to the ends of the honeycomb tubes. Indentation and

reinforcement procedures will also require study for these heavier walled insert rings.

3. Establish the effects of axial weld shrinkage from tube-to-tube joining on the tube-to-header weldments. Investigate prior tube tacking of the tubes to the header to maintain their desired positions, if necessary.

4. Determine the best method for locating fuel pin spacers in relation to the header during setup and welding.

5. Determine the necessary machining tolerances for the preparation of the header flanges, as required for producing the desired intertube stackup for tube-to-tube welding. This information would be of vital importance for the preparation of a full-scale nuclear reactor core structure having 200+ component tubes

When conducting these welding or processing experiments, other areas requiring study will no doubt become evident. Careful consideration should be given to the selection, planning, and performance of these and any associated tests to provide the most significant evaluation data with a minimal expenditure of effort. Although numerous realms of investigation still exist, many of the assembly requirements have been considered. The following procedural outline was therefore prepared based on those considerations to provide a tentative general guide for completing the construction of a model honeycomb assembly (further recommendations for testing are also indicated in the outline).

1 Machine a T-111 model header flange to the configuration necessary to produce tube-to-header welds (refer to Figure 52); counter bored holes on the rear side of the flange should be undersize to permit cleanup machining in those areas after tube-to-header welding. Dimensionally inspect the prepared component.

2. Prepare the T-111 dummy header flange, having the configuration shown in Figure 21. Note that the dummy header flange has an effective pyramid configuration on the side containing the counter-bored holes. This geometry will be advantageous for

the assembly of the tube bundle prior to welding.

3 Clean the machined model header and the previously prepared dummy header flanges per NASA Specification C-393666-2.

4. Heat treat the model header flange at 2400°F for 1 hour in vacuum per NASA Specification C-393666-3. Wrap the component in Cb-1Zr protective foil prior to heat treatment to prevent possible environmental contamination.

5. Position 19 honeycomb tubes with attached doublers on the model header flange, such that the bases of the extended doublers intersect with the top of the machined ribs in the header, the plane formed by the honeycomb tube ends should be 0 002 inch above and parallel to the top header surface (refer to Figure 52) An assembly tool will probably be required to properly locate the doublers indentations in relation to the header flange (refer to Figure 3). Inspect the tube bundle-header flange assembly to insure that desired setup positions have been produced. Wrap temporary Cb-1Zr straps around the bundle to maintain tube positions.

6. Insert the free end of the tube bundle into the counter-bored holes of the dummy header flange. Because of the pyramid surface configuration of the dummy header, each concentric row of tubes will intersect with the header at different intervals, starting with the center tube and ending with the outside row of tubes.

7 Mount the tube bundle-header assembly on the studs of the indexing plates, which are integral parts of the vertical supports of the weld positioning fixture (refer to Figure 22). Adjust the screw slide between the vertical supports to produce desired end-to-end support. Replace the Cb-1Zr temporary straps around the bundle with five hose clamps axially located over the doublers along the length of the tubes Prior to tightening the clamps, position protective tantalum foil strips under the clamps and insert short lengths of 0 25-inch molybdenum bar into the generally triangular

areas formed by the clamp and each pair of touching tubes in the outer row. Adjust the clamp pressure to produce the desired contact between the tubes along their lengths. Insert the gas-cooled welding torch through the dummy header flange in preparation for GTA tube-to-tube welding.

Achieving the necessary intertube contacts depends on the radial force exerted in clamping, as well as the location and number of clamps used Since these process variables were not explored in this program, it is recommended that experimentation be conducted to establish the best clamping conditions, as defined by the resultant tube-to-tube weld characteristics.

8. Transfer the weld positioning fixture, with mounted tube bundle, to the GTA welding chamber, connect welding power cables and other necessary electronic equipment. Verify that the desired conditions of travel speed, weld start and stop locations, electrode position, etc., have been set correctly. Evacuate the chamber, backfill with helium gas, and check to insure that impurities in the fill gas are at acceptable levels.

9 Weld the tube-to-tube joints, using the automatic internal GTA process, in accordance with NASA Specification C-393666-1 Make three center tube welds first, with the tungsten electrode located in the center tube. Reposition the electrode in one of the middle row tubes for the next welding operation.. Repeat the repositioning and welding operations, as required, to complete the tube-to-tube joining. Some of the other tube-to-tube processing details are as follows:

   a) Use a 0.040-inch diameter bent tungsten electrode with a sharp conical tip (refer to Figure 18).

   b) Set the electrode tip to weld surface distance at 0.04 to 0.5 inch.

   c) Initiate welding in each tube at the doubler located closest to the model header flange.

d) Use a start-stop-start technique to fabricate each tube-to-tube weld. Start and stop locations should coincide with the doublers positions along the axes of the tubes.

e) Use a welding current of 34 amps and a travel speed of 20 inches per minute.

It is recommended that the effects of varying the welding current during the actual cycle be studied to potentially establish conditions which would result in less distortion. The prior testing may indicate that tack welding of the tubes to the header flange would be necessary before starting tube-to-tube welding Also, only a specific number - less than 19 - of the tubes may be more advantageously joined before proceeding with tube-to-header welding.

10. Visually inspect the tube-to-tube welds with a borescope to determine their quality. Ultrasonically inspect typical welds for verification. Visually inspect the fit-up of the tubes with the model header to insure that the necessary conditions for fabricating tube-to-header joints have been maintained. These checks should be performed at various stages in the tube-to-tube weld processing As a further quality assurance measure, dimensionally inspect the overall assembly at different processing stages If objectionable torque or twisting of the tube bundle is noted, changes in the end-to-end support should be considered. Probable longitudinal weld shrinkage in the tube bundle may result in the separation of the model header flange from the tube ends. Compensation for that effect might be achieved, after completing the tube-to-tube welds, by the application of pressure (axial) to return the parts to their original relative positions. The validity of such processing, to produce the required tube-to-header fitup for subsequent welding, must be experimentally determined.

11. Remove the T-111 dummy header flange from the end of the tube bundle and perform final inspection of welds.

12. Automatically GTA weld the 19 tube-to-header joints in accordance with NASA Specification C-393666-1. Pertinent details of the processing are as follows:

   a) Use a 0.062-inch diameter bent tungsten electrode with a hemispherical tip (refer to Figure 24). Make a welding pass with the formed electrode on a dummy header specimen to insure that forming stresses have been relieved, prior to actual tube-to-model header welding.

   b) Set the electrode height to a point 0.005-inch below the top of the machined ribs (0.065 inch below the top header surface) in the header, set the radial tip-to-rib distance at 0.02 inch.

   c) Use a welding current of 100 amps, and a welding speed of 2 revolutions per minute.

The indicated sequence and procedures for fabricating the tube-to-tube and tube-to-header welds was based on the assumption that no prior GTA tack welding of the tubes to the header would be required. If previous support experimentation shows that processing step (tack welding) to be advisable, then the procedure might be as follows:

a) Mount seven tubes of inner hexagonal pattern on the header flange and tack weld extended doubler ends at two 180° separated locations to the internal header ribs.

b) GTA weld seven tubes together along their mutual contact lines.

c) GTA weld seven tubes to the header.

d) Add twelve outside tubes to the tube bundle, clamp in place, and tack weld to the header.

e) GTA weld these twelve tubes to their mutually adjacent tubes.

f) GTA weld these twelve tubes to the header.

COMPLETE HONEYCOMB ASSEMBLY

1 Visually inspect the tube-to-header welds with a borescope to determine their quality. Dimensionally inspect the overall model assembly at this processing stage to determine the extent of post-weld machining required, particularly in regard to the fuel pin spacers.

2. Machine the internal tube protrusions or fuel pin spacers to produce the required diameter at their nodal points (refer to Figure 2). Finish machining of the counter-bored holes in the model assembly header, machine the corresponding T-111 fuel element retainer rings to fit with the counterbored holes. Take appropriate measures to avoid contamination of the assembly during these operations.

3. Clean the retainer rings and the freshly machined surfaces in the model header flange by acid pickling per NASA Specification C-393666-3.

4 Place the welded tube bundle-model header subassembly, and retainer rings, in the electron beam welding chamber and weld per NASA Specification C-393666-2. Parameters to use in these operations require development.

5 Visually inspect the retainer ring-to-header electron beam welds to establish their quality. After removal of the hose clamps from the tube bundle, dimensionally inspect to determine final assembly machining requirements.

6 Finish machine the model assembly to the required dimensions and inspect for conformity (refer to Figure 2).

7 Clean the completed assembly by sequentially rinsing or flushing with reagent grade acetone, ethyl alcohol and deionized water. Immerse the assembly in Freon "TF" bath and ultrasonically agitate, remove the assembly, flush with Freon "TF", and sample the efflux liquid for particulate matter. Repeat these latter steps until the desired cleanliness levels have been attained, as indicated by a particulate matter ("dirt") count.

8. Place the finished assembly in a clean polyethylene bag and seal closed while purging with dry argon gas.

NOTE. The last two steps were not based on data from this study program, but rather on generally standard, commercially applied, contamination control procedures.

## IV. SUMMARY AND RECOMMENDATIONS

This study program demonstrated the feasibility of producing three weldment types required for honeycomb fabrication as described previously. Weld tooling was developed and demonstrated Weld joint strengths were also determined and proven adequate for the intended application

Two significant problem areas were identified. First, the tube-to-header weldment proved to be more difficult than anticipated. Although, 0.040-inch-thick wall T-111 tubes had previously been welded to headers,[3] the 0.010-inch-thick honeycomb tubes were much more susceptible to arc burn-back This condition was complicated by the tube-to-header joint clearances required to effect bundling for tube-to-tube welding The lack of intimate contact between faying surfaces increased the likeliness of uneven fusion.

Several iterations of joint configuration and stringent welding process control were required to produce defect free weldments repeatably. It is doubtful that all tube-to-header welds required for a full-size honeycomb core could be made with equivalent precision. It is therefore recommended that future multi-tube welding trials incorporate a heavier, i.e , 0.020-inch-thick tube insert, to improve welding process reliability.

A second problem area was the significant tube distortion associated with tube-to-tube welding trials The design conditions which required full-length weld attachment along the tube axes limited the techniques available for distortion control, such as intermittent welding. It is recommended that future welding studies include the doubler stations to provide distinct weld segments as well as start and stop locations.

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(3) Bond, J. A., ed. Topical Report: Design and Fabrication of a Three-Loop Advanced Rankine Cycle Boiler Test Rig, Contract NAS 3-9426 (To be published).

To summarize, this study established the feasibility of welding the three basic joint types required for T-111 honeycomb fabrication. These were tube-to-header, doubler-to-tube, and axial tube-to-tube welds. Visual, metallographic, and mechanical strength characteristics of each weld type indicated the basic acceptability of the techniques employed. Although weld tooling to perform model honeycomb fabrication was perfected, the full application of the welding processes was not realized. Additional fabrication trials will be required to fully qualify the welding processes developed.

## APPENDIX

## Program Plans

### A. Indenting and Reinforcing of Tubing Wall Doublers

Objective: To produce T-111 doubler insert rings which meet the Internal Tubing Projection requirements specified in the NASA Honeycomb Core Support Structure Drawing indicated in Figure 2.

Procedure:

1. Prepare tubing for inserts by cold drawing the 0.850-inch OD T-111 tubes to a final 0.827-inch OD.
2. Machine 0.500 ± 0.002-inch long rings from the reduced diameter tubing.
3. Dimple each of the machined insert rings to a fixed depth in the special indenting fixture (shown in Figure 14), using 5000 pounds load in a hydraulic press.
4. Clean each formed insert by acid pickling per NASA Specification C-393666-2.
5. Place inserts (15 each load) on special backfilling fixture (shown in Figure 15) in the vacuum purge welding chamber.
6. Cut 0.375-inch lengths of 0.062-inch-diameter T-111 wire for 0.033 to 0.034-inch deep indentations. Place the wire segments on a molybdenum bar and manually GTA fuse into a spherical shape.
7. Place formed balls of T-111 filler in the dimples and manually fusion weld per NASA Specification C-393666-1, holding the arc centered over the indented dimples until the molten metal conforms to the machined recesses in the molybdenum fixture. Use a 0.062-inch-diameter tungsten electrode and a welding current of 140 amps.
8. Rotate insert rings 120°, after the first 15 indentations arc backfilled, and repeat Steps 6 and 7 until all impressions have been reinforced.

9. Repeat Steps 5, 6, 7 and 8 to form and backfill 0.042 to 0.044-inch-deep indentations, except increase the quantity of 0.062-inch diameter T-111 filler metal wire to 0.5-inch lengths.

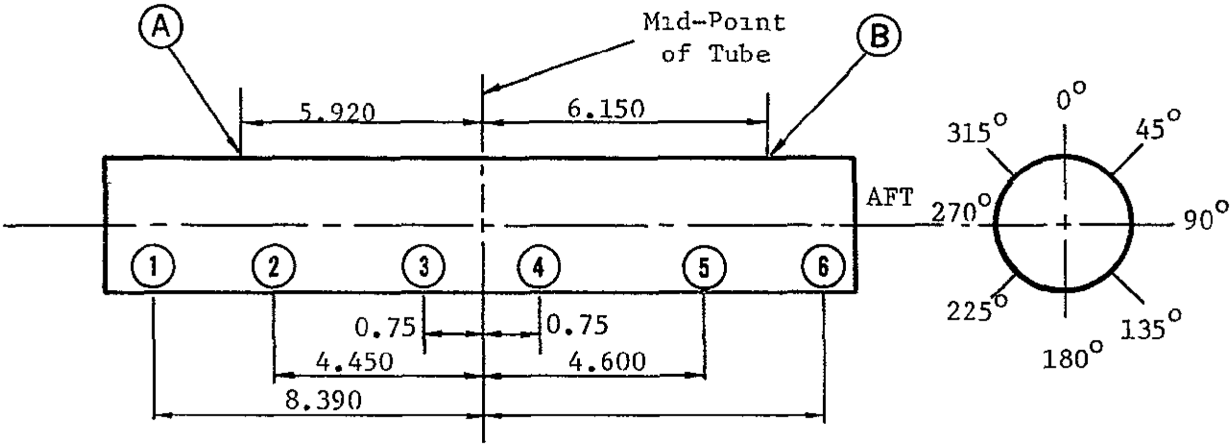
B. <u>Electron Beam Welding of Five Wall Doublers to a Full Length Honeycomb Tube</u>

Objective: To determine the extent of distortion in a honeycomb tube as a result of EB welding to attach five doubler rings.

Procedure:

1. Dimensionally inspect a 0.850-inch OD by 0.010-inch wall by 18 inches long T-111 honeycomb tube to establish its diametric and straightness characteristics. Inspection to be performed in accordance with the quality control plan shown below.
2. Clean five doubler insert rings and the honeycomb tube by acid pickling per NASA Specification C-393666-2.
3. Assemble five doubler rings on molybdenum expandable mandrel used in EB welding, and insert in the honeycomb tube.
4. Reinspect dimensionally as in Step #1.
5. Electron beam weld the five inserts to the honeycomb tube wall, per NASA Specification C-393666-4. Use two circumferential welds at each of the inserts, and three circle welds around the dimples at the center insert location only.
6. Reinspect dimensionally as in Step #1, before removal of the welding fixture.
7. Reinspect dimensionally as in Step #1, after removal of the welding fixture.

B.1 /Quality Control Plan - Dimensional Inspection of Individual Honeycomb Tubes




1. Scribe aft end face with degree marks every 45°. Mark zero degrees at aft end on OD approximately 1/8" from end.
2. Scribe an X at points A and B on the OD of the tube in line with 0°.
3. Use the shortest "V" blocks available and position the tube in the V blocks with the blocks centering at A and B.
4. Position points A and B at top dead center (zero degrees) and zero out points A and B by placing shim stock under the V blocks as required.
5. Measure and record the tube OD at points A and B at 0° and 90°.
6. With points A and B up, zero out an indicator and height gage (For the remainder of the checks do not change the indicator zero point.)
7. Move height gage to Points 1 through 6 at zero degrees and record the indicator readings as + or - from the AB zero setting.
8. Rotate the tube to 45° and again record the indicator readings as + or - from the AB zero setting.
9. Repeat Step #8 every 45°, recording indicator readings at points 1 through 6.
10. At points 1 through 6 measure the tube diameter at 0, 45, 90 and 135°.

## C. Gas Tungsten Arc Tube-To-Tube Welding

Objectives:

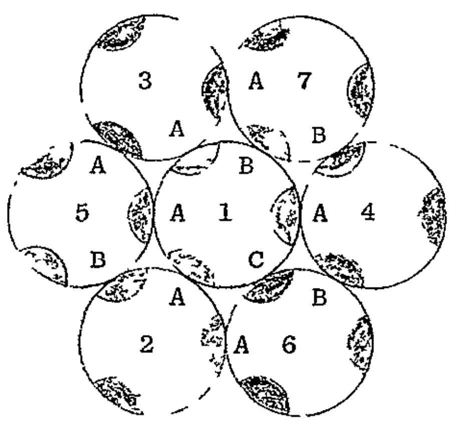
1. To determine the maximum clearance between T-111 tubes allowable during GTA tube-to-tube welding.
2. To document the effect of welds across doubler locations.
3. To determine the shrinkage and distortion which occurs in a seven (7) tube bundle during welding.

Procedure:

1. Machine or acid pickle a T-111 end support header until seven 0.850-inch OD by 0.010-inch wall T-111 tubes can be bundled with zero clearance at their intersections with the header.
2. Assemble seven (7), 6-inch tubes without doublers in a center cluster on the end support header.
3. Apply a strap at each end of the bundle, measure tube-to-tube clearances with feeler gages, and record.
4. Release the strap at the end of the tube bundle opposite to the header and place a 0.006-inch shim in one tube-to-tube joint to create an axially tapered joint clearance from zero to 0.006-inch.
5. Automatic GTA weld the tapered joint, starting at the zero clearance location, per NASA Specification C-393666-1. Perform the welding using the following parameters: 34 amps, 24 volts and a 33 inch/minute travel speed. Use a 0.062-inch diameter tungsten electrode with a sharp conical tip; set the electrode tip-to-inside tube wall surface spacing at 0.04-inch.
6. Repeat Steps #4 and #5, using varying shim thicknesses and total welding heat input, to define the maximum tolerable joint clearance.
7. After maximum allowable joint clearance and welding parameters have been established, assemble a second seven tube bundle (6-inch long tubes); each tube having two dimpled and filled doublers, electron beam welded in place. Weld one tube joint with maximum allowable joint clearance maintained with shims at both ends of the tube

bundle. Remove the two tubes welded for metallographic examination of the weld joint, particularly at doubler locations.

8. Reassemble the seven tube bundle with two replacement tubes and strap to bundle tubes as anticipated for fabrication of a model assembly. Measure and record tube-to-tube clearances with feeler gages, also measure and record tube length and bundle width across each 3-tube axis as a function of length.
9. Automatic GTA weld all tube-to-tube joints, making three (3) center tube welds first, then one or two weld joints in each of the outer tubes as illustrated below. After each weld is made use feeler gages to determine any change in joint clearance.




10. Inspect the seven tube bundle to determine distortion, shrinkage and weld quality.

D. <u>Gas Tungsten Arc Tube-To-Header Welding</u>

Objectives:

1. To determine the clearance between tube and header required for reliable weld joint.
2. To compare the clearance required for welding with the clearance required for bundling of tubes during tube-to-tube welding.
3. To produce tube-to-header weld joints for metallographic examination and strength evaluation testing.

Procedure:

1. Machine two (2) T-111 simulated header pieces, to the configuration shown in Figure 44c, to produce 0.0025 and 0.005-inch radial clearances between them and the ID of 0.827-inch OD by 0.010-inch wall tube inserts, at assembly. Dimensionally inspect to assure desired geometries have been produced. Clean header pieces by acid pickling per NASA Specification C-393666-2.
2. Clean six, 6-inch long honeycomb tube sections, and six, extended length, indented and backfilled doublers by acid pickling per NASA Specification C-393666-2. Electron beam weld each doubler to the honeycomb tube sections at specific end locations per NASA Specification C-393666-4.
3. Assemble one tube with doubler, and a simulated header, in the joint restraining fixture, schematically shown in Figure 31, using appropriate T-111 shim stock to produce a gather 0.005-inch clearance between the components.
4. Automatic GTA weld the specimen with 0.005-inch gathered clearance in the restraint fixture, per NASA Specification C-393666-1. Weld with the following parameters: 45 amps, 16.5 volts, and a travel speed of 7 inches/minute. Use a 0.062-inch diameter bent tungsten electrode, with a sharp conical tip. Position the electrode 0.035-inch-below the intersection of the header piece and the bottom of the extended doubler, and 0.040-inch away from the inside diameter of the machined rib in the header piece.
5. Repeat Steps #3 and #4, using the header component which produces 0.010-inch header-to-doubler clearance. Adjust welding parameters, dependent on results from previous trial.
6. Section and metallographically examine the prepared tube-to-header weld joints to establish weld quality and determine if parameter adjustments are necessary.

7. Machine four additional header components to produce the configuration most amenable to welding, and having the largest tolerable spacing, at assembly, with the extended doubler inserts ID surface.
8. Automatic GTA weld four additional joints in the restraint fixture to establish process reliability, using appropriate parts of processing Steps #3 and #4.
9. Compare results of tube-to-header welding study with clearance values obtained from engineering study of the tube bundling requirements in full scale assemblies. Recommend proposed approach to NASA Program Manager.
10. Machine three (3) tube-to-header tube joints to the selected configuration and GTA weld per NASA Specification C-393666-1.
11. Heat treat the specimens prepared in Step #8 at 2400°F/ 1 hour, per NASA Specification C-393666-3, and subsequently determine joints tensile properties.

## E. Electron Beam Fuel Pin Retainer Ring-To-Header Welding

Objectives:

1. To determine the electron beam parameters for producing sound fuel pin retainer ring-to-header welds.
2. To produce specimens for metallographic examination and strength evaluation testing.

Procedure:

1. Machine simulated retainer rings from T-111 bar per configuration shown in Figure 52.
2. Machine counterbore in single tube headers for retainer ring weld parameter tests.
3. Dimensional inspect and acid clean parts.
4. Electron beam weld the rings-to-headers as required to establish parameters, per NASA Specification C-393666-4.
5. Section and metallographically examine to determine penetration depth and optimum weld conditions.
6. Using the established best parameters, EB weld simulated rings in the three tensile specimens used for prior tube-to-header weld mechanical properties testing.

7. Postweld anneal the three test specimens at $2400^{\circ}F$/1 hour in vacuum per NASA Specification C-393666-3.
8. Tensile test the prepared specimens, using a pin (similar to fuel retaining pin) inserted in a machined groove of the rings for load transmission, and evaluate the results.

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